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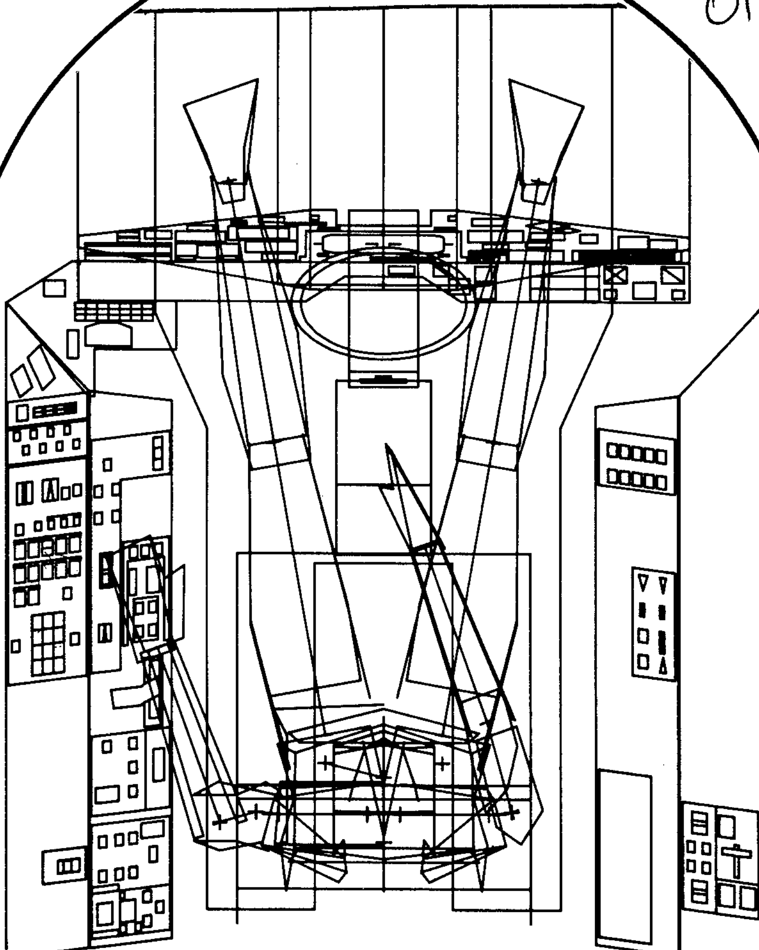

A DEVELOPMENT IN COCKPIT GEOMETRY EVALUATION

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A DEVELOPMENT IN COCKPIT GEOMETRY EVALUATION

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A DEVELOPMENT IN COCKPIT GEOMETRY EVALUATION*

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ABSTRACT

The overall problem of cockpit evaluation is discussed. Within this context, the specific problem of cockpit geometry evaluation is explored. Known methods for evaluating geometry (the physical layout of the entire cockpit complex–displays, controls, seats, personal equipment, windshield/canopy, interior surface shape, openings for ingress and egress) are summarized. Their advantages and disadvantages are presented.

The application of modeling techniques that take advantage of computer capability to improve geometry evaluation is discussed. A research program, in progress, directed toward the full development of a computerized model of the physical aspects of flight crewmen and any cockpit configuration is presented in some detail. This program, recently implemented, is a joint Boeing-JANAIR Program Working Group effort involving a combination of military, university, and industrial laboratories. Some early research results are summarized, along with initial validation efforts and techniques. New data requirements are also specified.

*Part of the research reported in this paper was accomplished under U.S. Navy Office of Naval Research, Contract N00014-68-C-0289, NR 213-065/11-16-67 (Code 461).

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Poor construction!!!

INTRODUCTION

Today, the cockpit subsystem design engineers and aircraft system operators, that is, military, commercial, and private organizations, must rely on design evaluation techniques that are limited by communication difficulties, inaccurate predictions, long flow times, and high cost. The fact that current cockpit subsystems, which comprise the man-machine interface, function as well as they do in the demanding missions of the various aircraft operators is a tribute to the adaptability of the flight crew, extensive flight-crew training programs, willingness of aircraft operators and aircraft manufacturers to absorb additional costs of retrofits, and dedication of career cockpit technology people. Fortunately, increasing research resources—both funding and people with the new human engineering skills—are being allocated for cockpit subsystem improvement. This, along with the slowly developing concept of treating the cockpit as a complete entity, integral to the aircraft, hopefully will advance cockpit technology as rapidly as general equipment technology.

As a manufacturer, The Boeing Company is attacking many cockpit problems. Long-range research is directed toward providing basic crew-performance data and developing improved design and evaluation tools for the cockpit engineer. One of the key research efforts concerned with cockpit evaluation methodology is presented in this paper.

This research effort is being conducted as a joint Boeing/JANAIR effort. The Joint Army Navy Aircraft Instrumentation Research (JANAIR) Program is a U.S. military research and development project directed toward providing the technical knowledge for improved mission effectiveness of future military manned aircraft systems.

To provide a background and context for the Cockpit Geometry Evaluation Research Program, we will first briefly examine the overall cockpit subsystem evaluation problem. It will be apparent that geometry is only one factor of the total problem, but its selection for an extensive research effort is a logical first step in providing the design engineer with needed, improved tools for use in design optimization. We will review current methods for evaluating cockpit geometry, bringing attention to their major advantages and limitations. We will then present the Boeing/JANAIR research program, including descriptions of the computer routines and the modeling techniques being developed for the crew-station geometry evaluations.

THE COCKPIT SUBSYSTEM EVALUATION PROBLEM

Cockpit evaluations are performed in every phase of system development to assist aircraft operators and manufacturers in determining the degree to which objectives are achieved. Evaluations are performed on elements, components, subsystems, and total systems, and cover both equipment functional performance and flight-crew proficiency. The evaluation may continue until system degradation, or destruction, is reached. The validity of these evaluation results depends on five factors: (1) integrity, skill, and experience of the evaluator; (2) adequacy of the criteria; (3) limitations inherent in the evaluation methods used; (4) control of the test conditions; and (5) availability of test equipment.

Depending on aircraft system study objectives and requirements, the stage of cockpit subsystem development, and the complexity of the factors involved, many different methods and procedures may be used to implement the evaluation. A wide variety of analytical methods is initially employed to investigate missions, tasks, action/information requirements, functions, operations, workload, design layout, weight, cost, stress, hazard, and quality. As crew-station development progresses, the types and amounts of simulation advance from general analytical techniques, supplemented by computerized mathematical models, to mockups, fixed- and moving-base dynamic simulators, and special test rigs of many descriptions and degrees of sophistication.

In general, all the methods that try to examine crew performance, both mental and physical, have some limitations. Those that can be applied early in a design program, for example, activity flow diagrams, mathematical models, and mockups, are limited in prediction accuracy. In addition, they are subject to the bias of the analyst and lack standardization of input data, method, format, and output descriptors. The more precise methods, such as full dynamic flight simulation and prototype flight test, occur so late in the product development program that any needed redesign indicated by them is usually costly, since designs are frozen by this time and manufacturing commitments made. Thus, early in aircraft programs, when it is simple and cheap to redesign, we usually are not smart enough to optimize the cockpit subsystem. We must take a calculated risk when freezing the cockpit design. At best, if we are fortunate, we may run some part-task flight simulation studies prior to design freeze and preliminary full-flight simulation tests just after.

Aircraft operators have additional conflicts beyond those experienced by the manufacturer. The military, airline, and private operators have to select cockpit designs from a variety of manufacturers competing for their business. Usually this selection must take place prior to prototype flight. Thus, not only

must the aircraft operator organizations make expensive commitments based on the output of limited evaluation tools, but they must understand in detail a large number of different evaluation tools, variations on these unique to each manufacturer, special tool limitations, and the particular analyst bias that can be implicitly integrated in each method. These difficulties, under present conditions, leave neither the aircraft operators nor the aircraft manufacturers in a good position to make a responsible evaluation of a proposed cockpit subsystem. All would greatly benefit if standardized methods were developed and validated for accurately evaluating the cockpit subsystem early in aircraft system design programs.

It is not surprising to find that crew-station evaluation creates problems for project managers, system designers, and developers. Problems are encountered in determining what, how, and when to evaluate, and the form that results should take. They arise because:

- Nothing clearly defines the critical evaluations that must be performed in each phase of crew-station development or the relationship between individual evaluations.

- Nothing specifies the best technique to follow in accomplishing an evaluation.

- Nothing specifies the required form or content of an evaluation to ensure compatibility with the needs of the users.

Devising a solution to the crew-station evaluation problem will not be a quick and easy task. Standardized methods must be developed and implemented on all aircraft programs. The development of these methods should be oriented toward the concept of an overall single figure-of-merit rating for the cockpit subsystem. What cockpit factors should comprise the figure of merit, what methods are best for determining each factor, and how these factors should be weighted and mathematically combined to form the figure-of-merit have yet to be determined. Some of these factors and a flow diagram suggesting a gross relationship are shown in Figure 1. The heavy, dark line through the flow chart indicates a path of influence for a basic set of evaluation factors. For example, along this line, physical factors are combined into crew physical performance, which becomes a factor of crew task performance. Crew task-performance factors influence the effectiveness of the crew station. The other associated evaluation aspects—crew-station effectiveness and cost effectiveness (represented by the cutoff sequences that join the heavy line)—are grossly presented to indicate critical relationships.

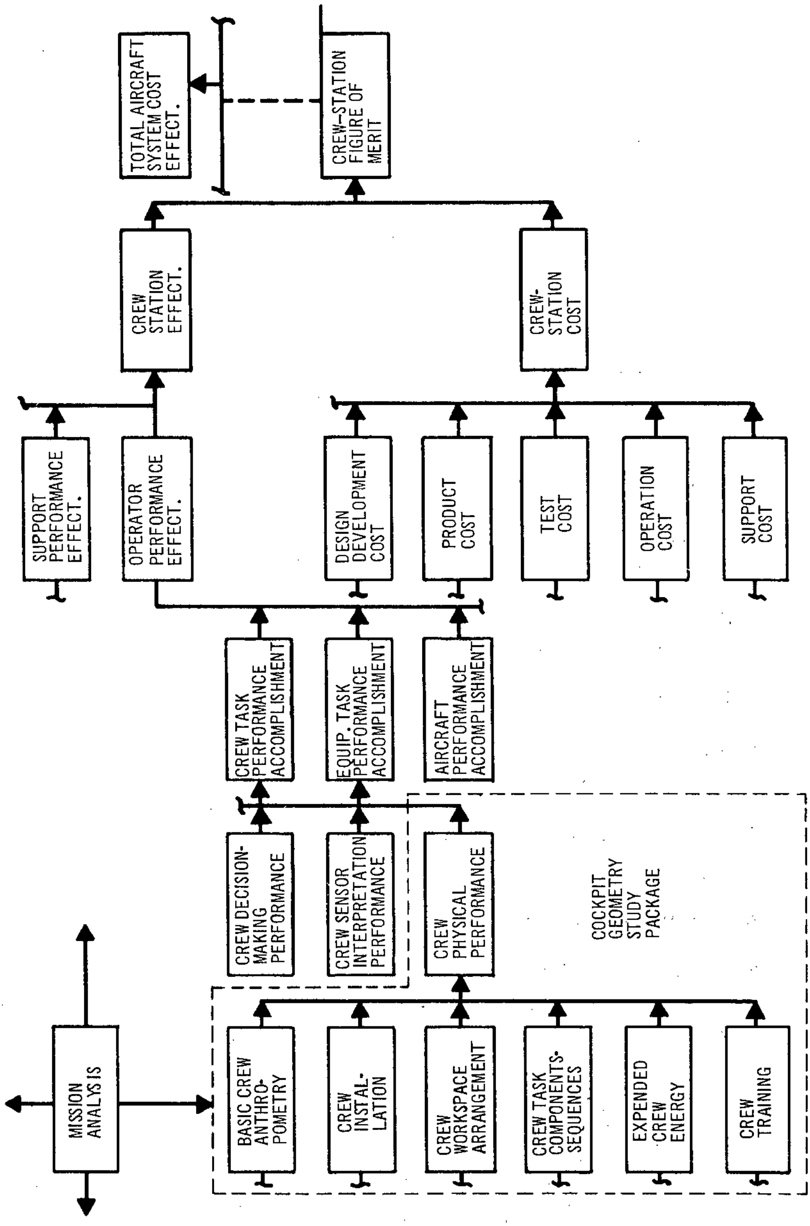


Figure 1. *Abbreviated crew-station evaluation flow diagram*

It is not accidental that a breakdown of the crew physical performance factor is presented in Figure 1. This is the one performance-oriented factor that most specialists in the cockpit technology area agree is likely to retain its identity in any listing of factors. The two other key factors, included in Figure 1, tentatively identified as "sensor interpretation" and "decision making," do not have this degree of agreement. Thus, while the research effort for exploring the factor identity and problem breakdown associated with a total cockpit/crew performance figure of merit has yet to be defined, a methods development program to improve cockpit geometry evaluation has been instituted as a useful first step that will have long-range application to the development of a cockpit subsystem figure-of-merit concept. A preliminary logic flow that illustrates the elements involved in the evaluation of cockpit geometry is presented in Figure 2.

At the onset of this program, it was determined that the method to evaluate cockpit geometry through crew physical performance should:

- Be applicable in all stages of crew-station development from concept to actual operations
- Provide a common reference by which to compare the physical parameters of operator/crew-station layout
- Permit specific items of interference with crew performance to be identified and indicate areas where improvement will be most beneficial
- Produce repeatable results regardless of the investigator
- Produce results in a form that is applicable to either program management or design development decision
- Permit evaluation to be accurately performed with a minimum of time and expense
- Be validated by test
- Permit the evaluator to consider dynamic motion with real-time effects, variations in operator size, simple and complex actions, and physical restraints

The need for real-time evaluation of cockpit geometry deserves a brief discussion. It is generally considered that a thorough evaluation can be accomplished in non-real time. If a control can be reached and operated easily in a mockup, then it is usually graded acceptable. This non-real-time approach, while certainly useful and simple to accomplish, cannot be considered to be a total evaluation.

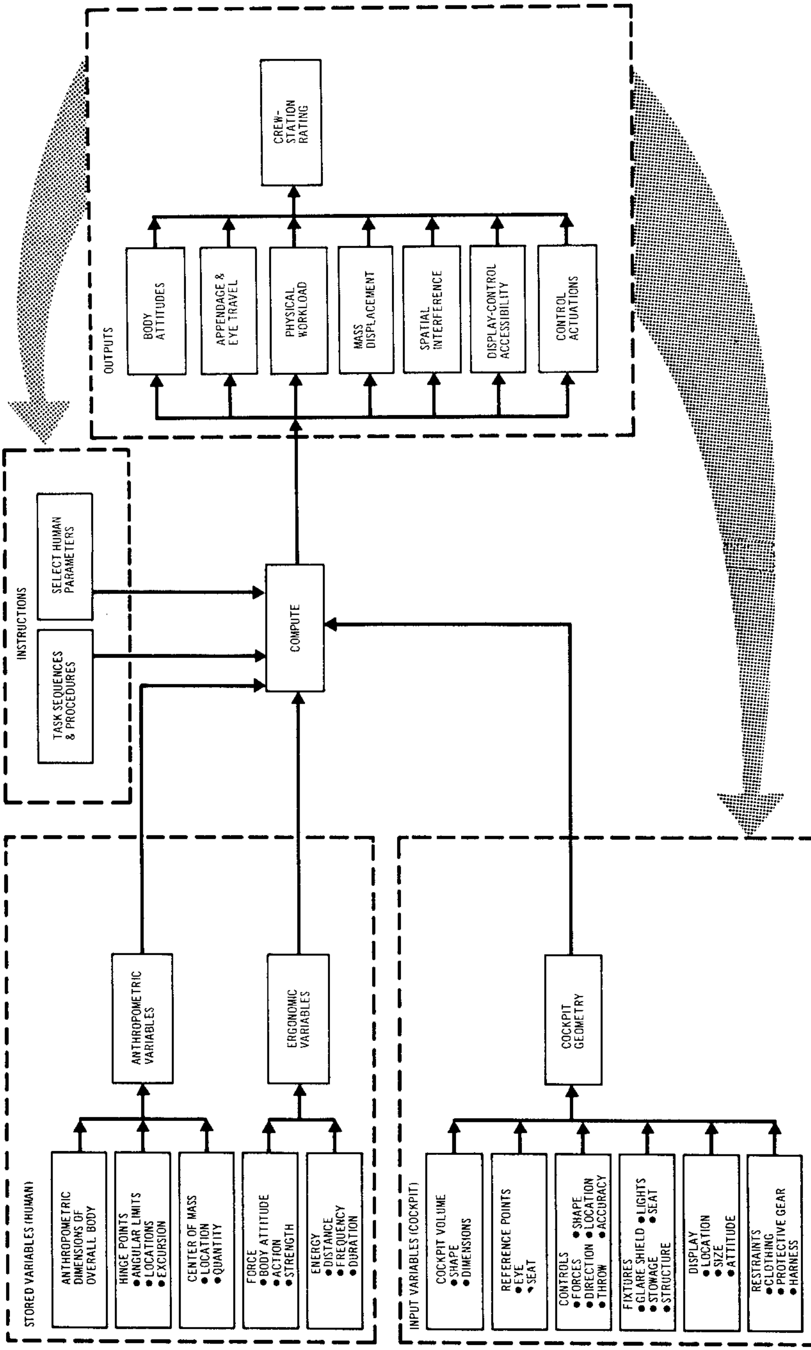


Figure 2. Crew-station geometry evaluation logic

Each cockpit subsystem contains some controls and requires some specific viewing positions that are associated with the performance of critical tasks. These controls and viewing areas must be readily and rapidly accessible, and the controls must be actuated under the high stress conditions associated with critical tasks. Critical operations, of which emergencies are one class, are usually examined in terms of time available to accomplish them. However, the time available, in most cases, is defined as "as fast as you can do it." Thus the time available to actuate a critical control can be treated as a physical limit problem.

Consider the effect on cockpit geometry when crewmen are operating with a minimum of time for task execution. The critical controls being actuated must have maximum tactile signatures and exaggerated clearances. They must be readily accessible, require a minimum of body distortion, and be free of interference from other elements in the cockpit.

Thus, the method for providing a complete evaluation of cockpit geometry must account for the movement limit velocities associated with the various anthropometric and ergometric combinations of the crew population. The method must recognize that these limits will be a function of (1) the anthropometry, (2) the appendage location in space at the time a maximum velocity movement is required to attain a new spatial position and to perform a specific critical control task, (3) the spatial location of the control (knob, toggle, stick, lever, etc.) to be actuated, and (4) the control shape, throw, throw force, and setting accuracy.

COCKPIT GEOMETRY EVALUATION

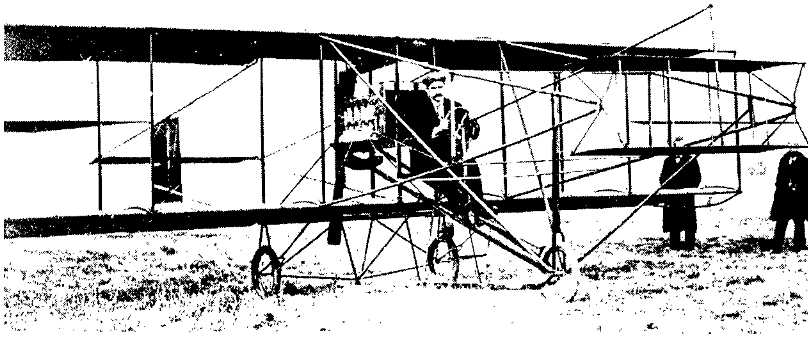
Cockpit geometry is defined as the physical layout, that is, locations, shapes, forces, and arrangements of the entire crew-station complex–displays, controls, seats, personal equipment, windshield/canopy/windows, interior surface shape, and openings for ingress and egress. Cockpit geometry has evolved from the minimal display and control arrangement of the open aircraft to the complicated arrangements in many of today's aircraft (Figure 3).

Currently, drawing reviews, mockups, mathematical models, flight simulators, and prototype flight-test techniques are used to evaluate cockpit geometry. These methods have been refined over the years and do produce useful data, yet they cannot take into account the full variability in flight-crew anthropometry. Figure 4 attempts to illustrate this problem and the associated penalties of flow time and cost for, in this case, the Military. Geometry evaluation has additional limitations, since dynamic evaluation requirements are not met until flight simulation and flight tests are conducted. This usually occurs too late in a product program for easily implementing any needed redesign. Thus, the industry still produces cockpit subsystems with geometry problems. Some problem examples are cited in references 1 and 2.

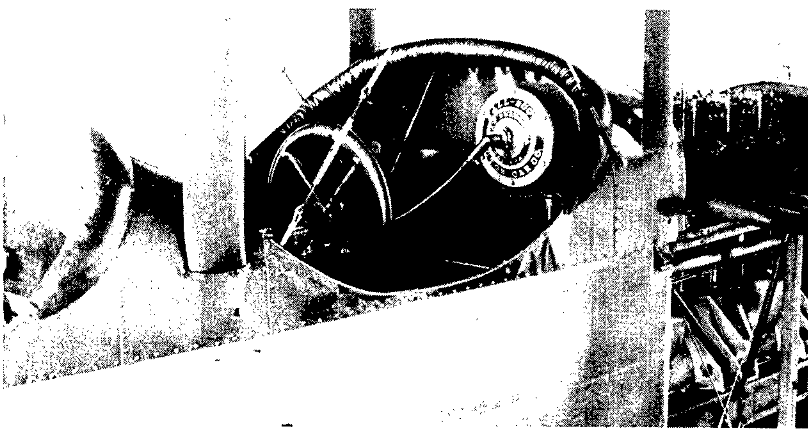
Drawing Reviews

Geometry evaluation, using information on cockpit drawings, usually consists of comparing proposed dimensions and display/control positions with those recommended in military and FAA standards and specifications. Handbooks, such as the Air Force Handbook of Instructions for Aircraft Design (HIAD), are used, along with basic anthropometry tables to provide detail criteria. A few special tools have been developed to reduce the flow time and cost of these reviews. Slide rules that summarize anthropometric data and two-dimensional manikins (Figure 5) that can be quickly adjusted to flight-crew population limits have become an accepted part of the cockpit engineer's tool kit.

(A)



(B)



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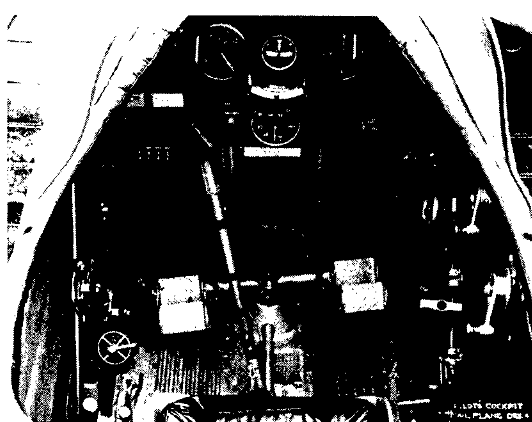
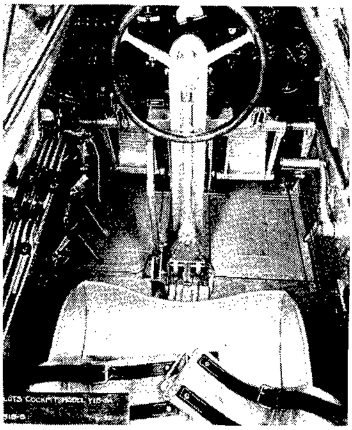


(A) 1910: CURTISS PUSHER

(B) 1916: BOEING B-W SEAPLANE

(C) 1928: BOEING MODEL 40C

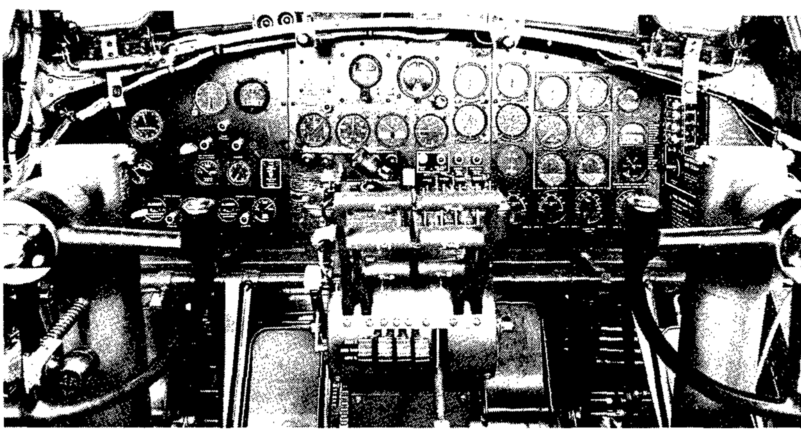


(D)

(D) 1932: BOEING YIB-9A

(E) 1944: BOEING B-17G

(F) 1960: BOEING B-52



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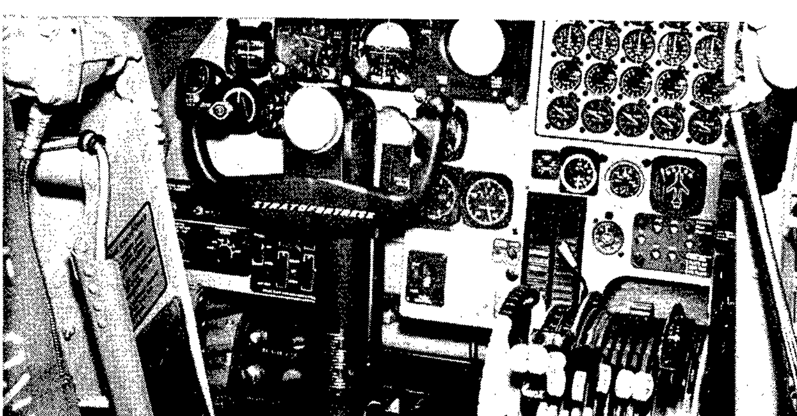


(F)

Figure 3. Cockpit geometry evolution

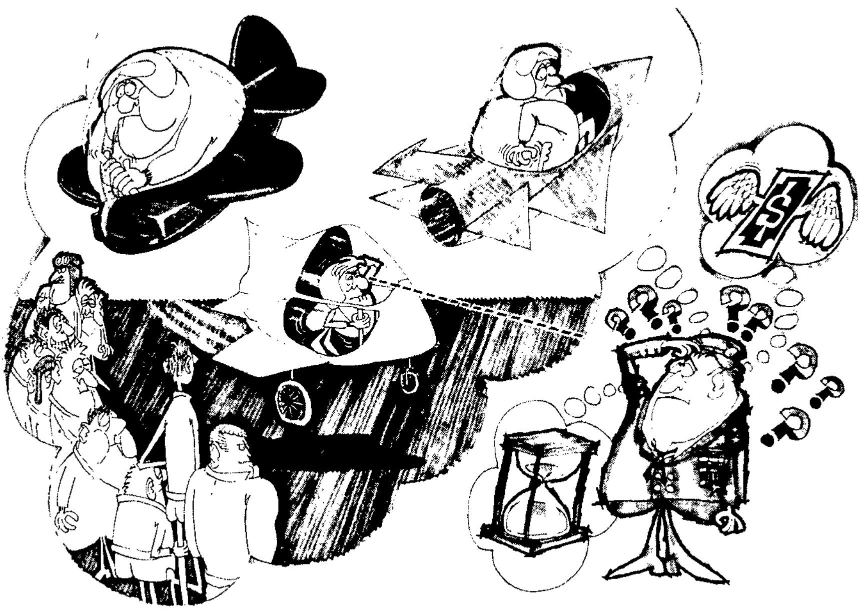


Figure 4. *The problem*

Link analysis is sometimes performed as a part of the drawing review. This technique is quite laborious and tedious to apply for each geometry concept being evaluated, and, as a result, is not used as often as it should be. Today, however, it is the only way we have of measuring crew physical workload. This analysis identifies most-traveled links, both visual and crew appendage, between the various cockpit subsystem elements. It can also provide a summation of total appendage and eye/head deflection travel as a function of mission task. Thus, link analysis, properly performed, is the basis for optimizing the location of cockpit elements in terms of minimum crew physical activity.

Drawing reviews are useful for preliminary evaluations. They provide the only evaluation data early in design programs, and many geometry errors are identified by this simple method. The method is limited by the evaluator's ability to visualize three-dimensional dynamic flight-crew physical activity, by the time required to draw special views, and by the engineer's ability to apply the large mass of anthropometric and ergometric data.

Mockups

Mockups supplement drawing reviews. They are excellent communication tools for review teams, and permit evaluators to try out a design concept. Evaluators can easily simulate, in non-real time, the intended physical task sequences of flight-crew members and can more easily identify cockpit geometry problems with mockups than with drawings. The mockup is an indispensable tool for cockpit engineers.

The dollar and flow-time costs for mockup construction have slowly improved over the years. Three materials are generally used for mockups today: metal, wood, and Fome-Cor*. The comparative costs of simple tandem cockpit mockups made of each material are summarized in the following table.

Material	Man-Hours	Material Dollars
Fome-Cor	300	300
Wood	1500	500
Metal	3400	750

The Fome-Cor mockup technique was developed in the early 1960's, primarily by Tom White of LTV, Inc. This type of mockup has become the first mockup for geometry evaluation at Boeing. Figure 6 shows Boeing's advanced crew-station laboratory, which relies on Fome-Cor for all mockup activity. This laboratory, through the efforts of William Bullock and Harleston Hall, Jr., has refined construction techniques to minimize labor and flow time. Preliminary mockups can now be made available for cockpit geometry design support with little lag time from the drawing board.

A promising trend is starting where preliminary geometry layout drawings are being made initially on Fome-Cor and cut out for mockups. These mockups are then easily refined on the spot, with the stroke of a knife or taped and glued attachments, to fit a selected sample of flight-crew members. The result of this activity, an acceptable preliminary cockpit geometry concept, is transferred to standard engineering drawings, thus saving many concept selection and design improvement drawing cycles.

As useful as mockups are, it is still not possible to thoroughly evaluate cockpit geometry through mockups because people representative of a wide variety of human anthropometry are not available to exercise the mockup.

*Registered trade mark

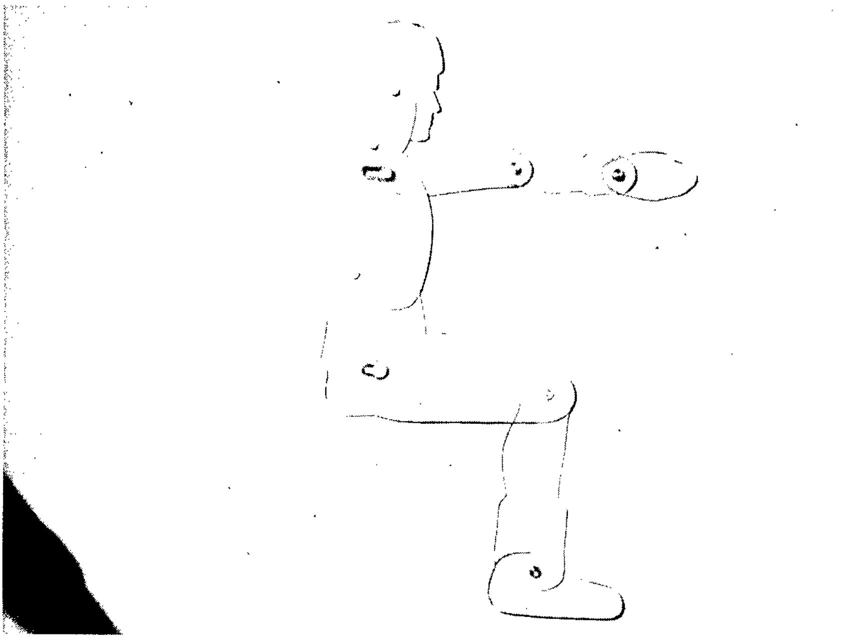


Figure 5. Typical two-dimentional manikin used to simplify cockpit drawing reviews

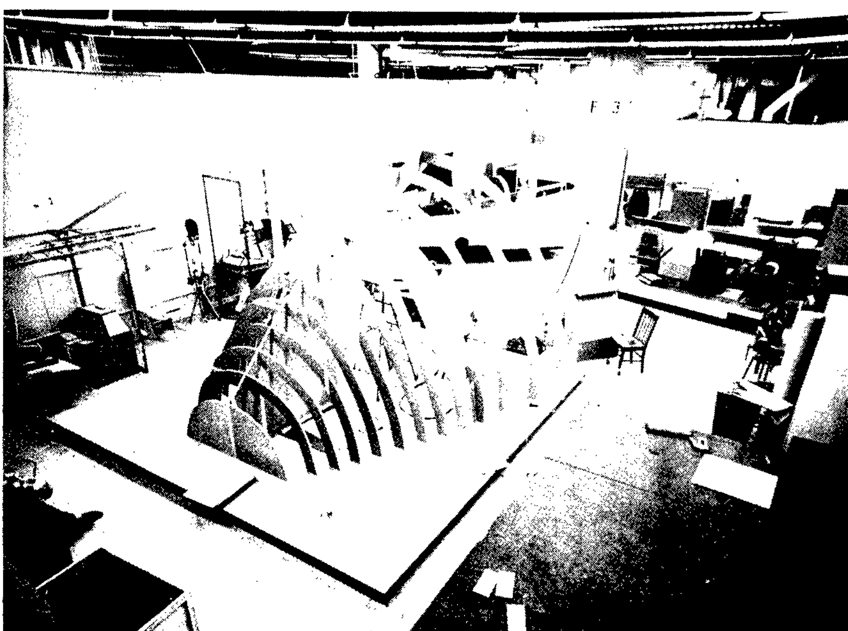


Figure 6. Extensive use of Fome-Cor mockup techniques in the Boeing advanced crew-station laboratory.

Mathematical Models

Little work has been done to develop mathematical models useful for cockpit geometry evaluation. The concept of capitalizing on digital computer capability for handling cockpit models is a comparatively recent one. Computers have been used as an aid to the operation of the cockpit subsystem for years, but their use as an aid to cockpit design and evaluation is just beginning. In the early 1960's, Art Siegel of Applied Psychological Services under an Office of Naval Research contract initiated a significant model development effort oriented toward evaluating the cockpit subsystem (3). A simple form of geometry evaluation is included in Siegel's model in the form of crew action time to operate various controls. This basic model was expanded by Boeing (4) to include 10 interacting crewmembers, a save-and-return technique that allowed the simulated crewmember to branch his or other crewmember action sequences to a required side activity and on completion return to his primary action sequence, multiple branching, a more descriptive language for the input format, and a change from an assembly language to a FORTRAN stored program. The Boeing mathematical model was used experimentally to support preliminary aircraft design programs to determine the usefulness of this approach. Some design benefit was derived and the approach was determined to be promising. However, it became apparent that much more research was needed before models this complex would become an accepted tool for cockpit engineers.

Based partly on this experience, a new activity was started by Pat Cleary of Boeing to develop a measure of only crew physical workload in the Boeing 737 transport cockpit (5). A simple two-segment (arm and eye) man was modeled and programmed into a digital computer. The 737 windshield, displays, and control locations in the cockpit were programmed, as were the expected task sequences of the two flight-crew members. The computer program was processed to provide preliminary cockpit geometry evaluation data in terms of total hand travel and angular deflections of the eyes for a mission. This useful output was a measure of physical workload as a function of the limited geometry simulated by the computer. For the first time, variations of display-control locations and crew procedures could be quickly evaluated against explicit criteria to determine an optimized layout.

Application of these computer techniques was encouraging and resulted, in part, in computer graphics research to present evaluation results in pictorial form, thus enhancing the usefulness of evaluations. A seven-segment man-model was developed by William Fetter of Boeing, and realistic movements obtained. The result consisted of computer-made movies of a simulated human form making simple movements in a manner similar to a pilot.

Thus, simple geometry evaluations using computer techniques are starting to be used to support cockpit design efforts. The promise of having a method for precisely measuring physical workload against explicit, meaningful criteria has

yet to be fulfilled; however, a significant first step has been achieved.

Flight Simulators

There are many classes of dynamic flight simulators, ranging from computer graphics to full-size moving-base test rigs. Currently, the full mission flight simulators provide the best way to evaluate cockpit geometry. A more realistic setting for simulating flight-crew physical activity is provided in real time. For example, full mission simulators demand the real-time physical activity required by a cockpit design with a minimum requirement for the flight crew to pretend or act out mission performance. Simulators suffer the same sample-size limitation of mockups, take longer to build, and have a higher dollar cost. As much as ten million dollars can be invested in a realistic moving-base mission simulator facility to support an aircraft system design program.

Research has provided some preliminary solutions to the flow time and dollar problems. Most notably, the recent use of computer graphics to simulate flight-crew fields of view and display operation offers promise. Much of the early work to develop dynamic computer graphics techniques for windshield geometry and display evaluation was done by William Fetter of Boeing. Figures 7 and 8 show samples of computer-generated windshield and display scenes. Other organizations, such as Bell Telephone Laboratories, are also currently continuing research to optimize computer graphics. Some day this technique will be a common computer output tool for the cockpit engineer. The computer, in real time, will pictorially reveal motion and shape problems that are otherwise concealed in masses of data.

To summarize, it is apparent that the current methods of evaluating cockpit geometry require improvement. A standardized method needs to be developed that will permit the cockpit engineer to easily and accurately apply all anthropometric and ergometric data as early in aircraft design programs as the preliminary mockups. It is believed that the solution lies in taking full advantage of digital computer capability to simulate a flexible man-model, any cockpit geometry, and crew physical procedures associated with the geometry and the mission to be performed. Boeing has demonstrated the use of a simplified version of this model approach as a part of the 737 cockpit evaluation. Also, a seven-segment man-model has been programmed to illustrate human movements through computer graphics techniques. A 17-segment man-model is now being programmed to illustrate additional movements and thereby improve evaluation results. The computer capacity, programming technology, and a large part of the anthropometric data required for the development of a fully articulated man-model are available. The modeling and development of computer routines to describe cockpit geometry will be an expansion of present capabilities. A sizable amount of development effort is required, however, to provide the mathematical model for simulating human movements. It is to this end that the Boeing/JANAIR program is oriented.

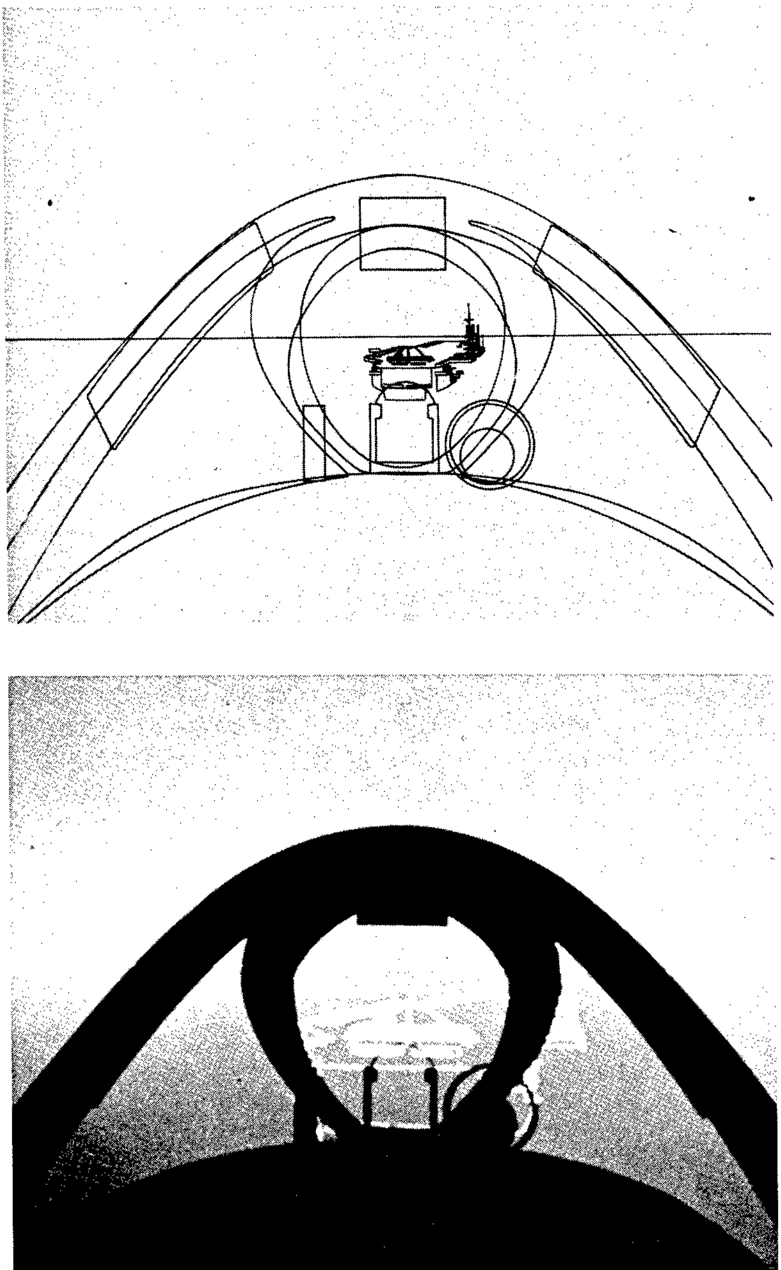


Figure 7. Excerpts showing computer graphics application to windshield/canopy field-of-view evaluation

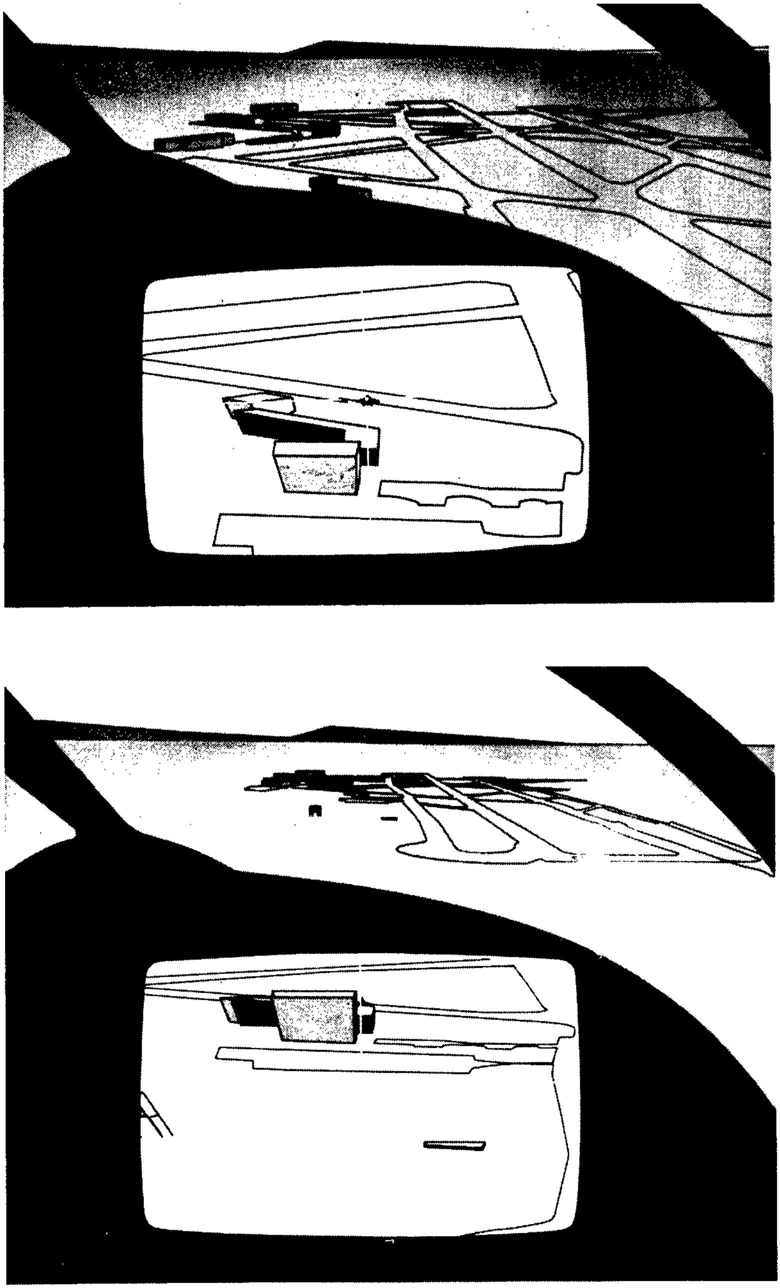


Figure 8. Excerpts showing computer graphics application to TV display evaluation

BOEING/JANAIR COCKPIT GEOMETRY EVALUATION RESEARCH PROGRAM

The development program is planned for six phases, each of 12 months' duration, as shown in Figure 9 (6). The program is a joint experimental laboratory, computer modeling, and flight simulator and actual flight test validation effort. Each year of effort will provide an end product of immediate use to military and civilian designers. The first year provides a baseline model using a 23-joint, pin-link "stick pilot" called BOEMAN-I (Figure 10). The next year will put skin volumes on the "stick pilot" to provide the three-dimensional BOEMAN-II, and improve the definition of cockpit control volumes. The third year will incorporate joint-center excursions to BOEMAN-III. The fourth year will add some force and control grasping capability to the "pilot," incorporate the preferred positions for dexterity and an extension capability to some joints to form BOEMAN-IV, and improve the definition of cockpit control shapes. During the fifth year, additional force vector variables and selected energy expenditure variables will be incorporated into the computer program to form BOEMAN-V. Finally, the sixth year will provide a skin deformation capability and additional energy expenditure variables for BOEMAN-VI. At this point in time, a fully articulated, realistic "pilot" model will have been validated and programmed into the computer along with cockpit dimensions (including display-control locations) and realistic shapes of all its elements.

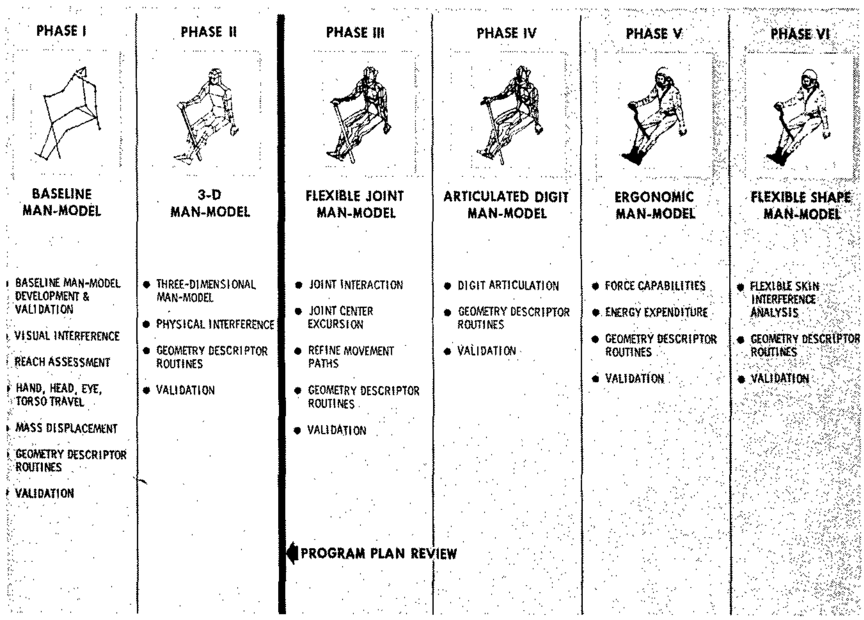


Figure 9. Research plan summary

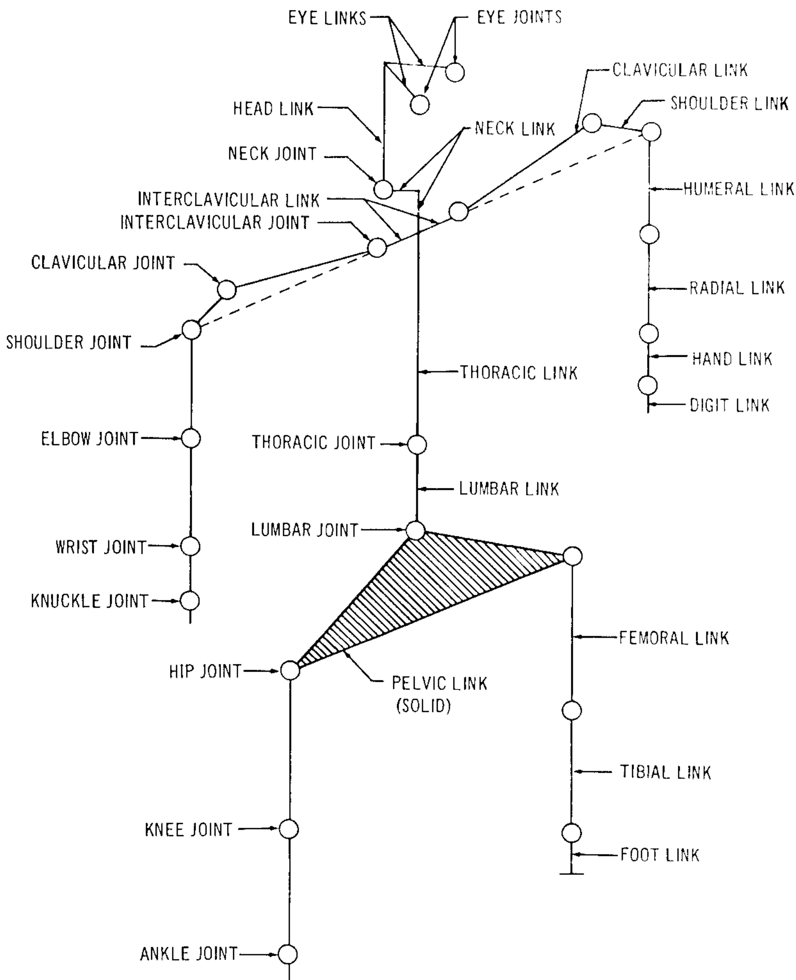


Figure 10.   BOEMAN-I baseline 23-joint flight-crew model

This resulting fully articulated computer model will be able to evaluate cockpit geometry in terms of any human anthropometric combination, any set of flight-crew task sequences, and any set of cockpit geometries. The flow of information for accomplishing the cockpit geometry evaluation is shown in Figure 11. The computer will supply useful predictions concerning:

- Display-control accessibility
- Control actuation
- Workload in terms of energy expended, body mass displacements, and distances traveled by the flight crew's eyes and each flight-crew appendage

- Interferences between flight crew and the cockpit structure/equipment and interferences between flight-crew appendages
- Design changes required to make the cockpit subsystem compatible with flight-crew physical capabilities

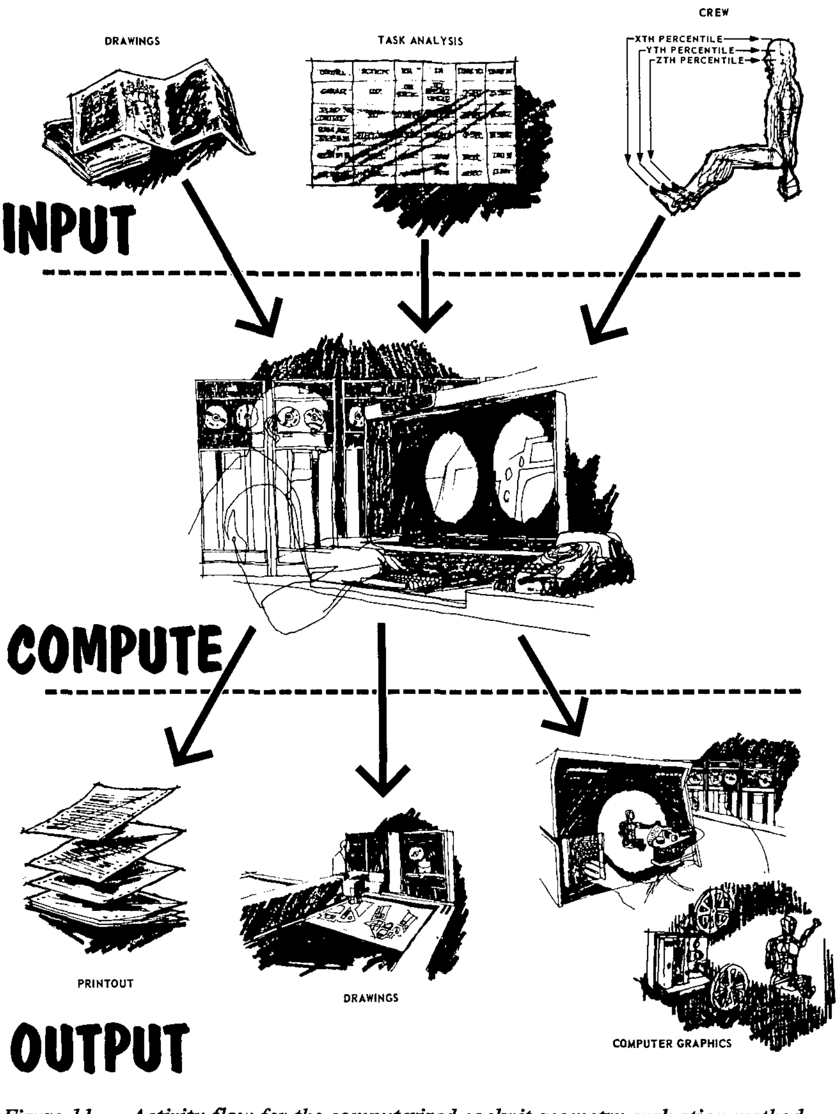


Figure 11. Activity flow for the computerized cockpit geometry evaluation method

Phase I

The Phase I portion of the program is scheduled to be completed by January 1969. The accomplishments of Phase I will include:

- A baseline cockpit geometry evaluation computer progr m that incorporates a mathematical model (man-model of a 23-joint articulated stick-man (BOEMAN-I)) of any desired size
- Anthropometric data to describe the linear dimensional characteristics and angular excursion limits of the United States pilot population
- Laboratory data describing joint movements during typical flight maneuvers, as well as validation of BOEMAN-I against these data
- The development of computer-controlled communication techniques to automatically display evaluation results in tabular form, in curvilinear and bar graphs, and with alphanumeric notation.

The discussion of Phase I includes information concerning management, computer hardware, the computer program, validation, and new data requirements. The major portion of Phase I is directed toward the establishment of a feasible mathematical model (man-model) of a human operator and related sections of a computer program. Thus, much of the following discussion centers about the computer program development.

Management

The management contrôl of the Phase I portion of the Cockpit Geometry Evaluation Program is effected through the use of a modified Program Evaluation Review Technique (PERT) chart. This diagram is shown in Figure 12. The flow chart indicates the interaction of the various elements being developed, the amount of time, in weeks, required to develop each element, and the latest date the item can be made available in order to effect required progress. This procedure and similar techniques have been used for some time in the control of production programs, but little use of the method has been made to plan and control research projects.

Experience with this method of managing the Boeing/JANAIR research program is providing encouraging results. The many separate but related small research tasks have remained on schedule, coordination among the task teams is being maintained, and trouble areas are being spotted and resolved in a timely fashion. Forcing visibility of the program elements will continue throughout future phases of the program. The PERT chart technique is an important tool, and can successfully be applied to research programs.

Computer Hardware

The computerized man-model is being coded for processing on a CDC 6600 computer. This computer was selected because the capabilities of the

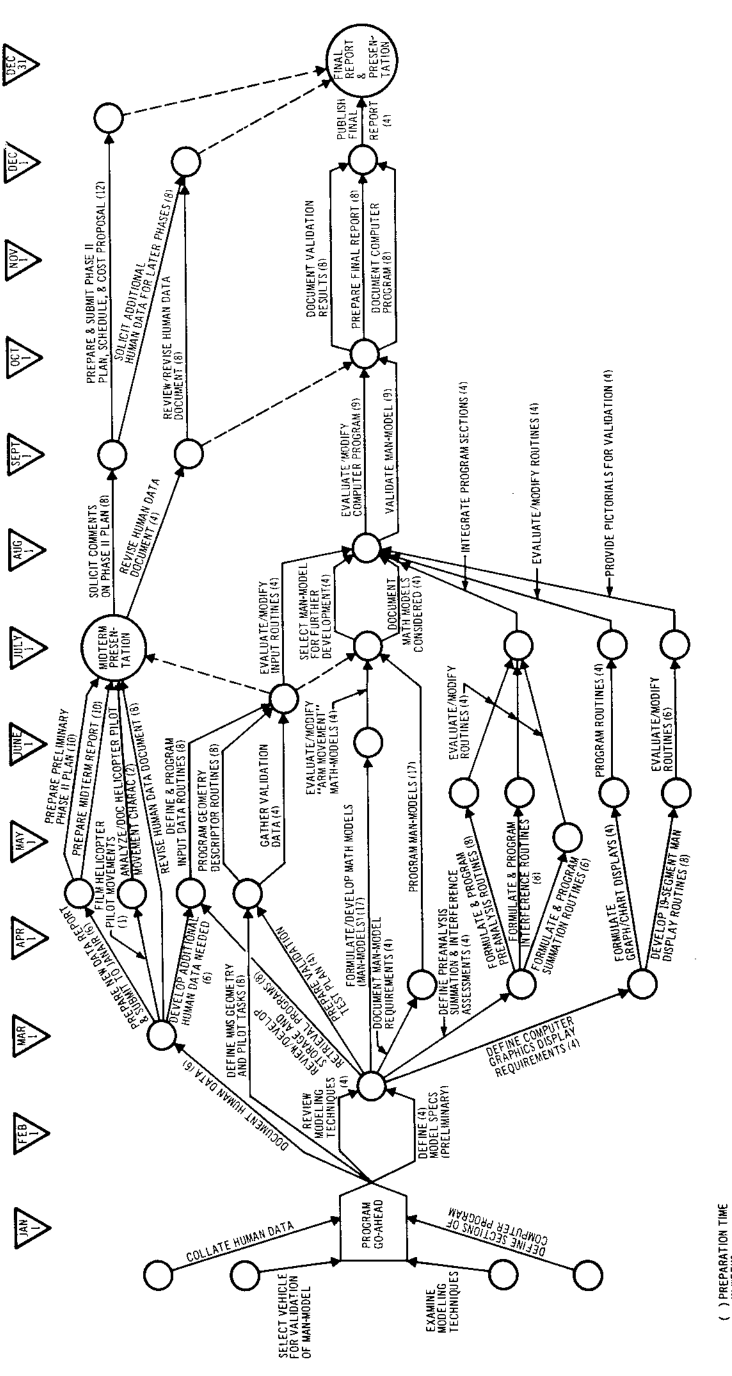


Figure 12. Cockpit Geometry Evaluation Program—Phase I, Baseline Man-Model

machine were most compatible with the requirements of the evaluation method under development. These requirements include:

- Large storage capacity to facilitate handling of large quantities of input and output data
- Low execution time to minimize computation cost
- Operating capability with a universal computer language such as FORTRAN.

The CDC 6600 also offers previously developed subroutines for the storage and retrieval of data, thus eliminating the need to develop such routines for the CGE project.

The storage capacity of the CDC 6600 has not been taxed as yet with the computation performed during the checkout of various sections of the Phase I computer program. The entire computer program for the CGE project has not been integrated and, therefore, the total storage capacity requirement is yet to be determined.

Computer Program

The end product during each phase of the project will be a computer program to effect an evaluation of the geometry of a work station. The computer program has been modularized to facilitate the development of BOEMAN-I and the subsequent modification of this model in later phases of the project.

The major portions of the computer program include the (1) input, (2) stored variables, (3) compute, and (4) output sections. The flow of information is shown schematically in Figure 13.

The input section provides the means to specify operator physical parameters, geometry, and the task sequences required by the cockpit for mission fulfillment. The stored variables section minimizes the human and geometry parameter coding required by the input section. The compute section, the key to the success of this evaluation method, uses the human and geometry parameters to determine man-machine physical compatibility by simulating the movements that would be made by real crew members operating the particular cockpit being evaluated. The output section displays the results of an evaluation or a series of evaluations. Each of these sections is discussed in greater detail in the following paragraphs.

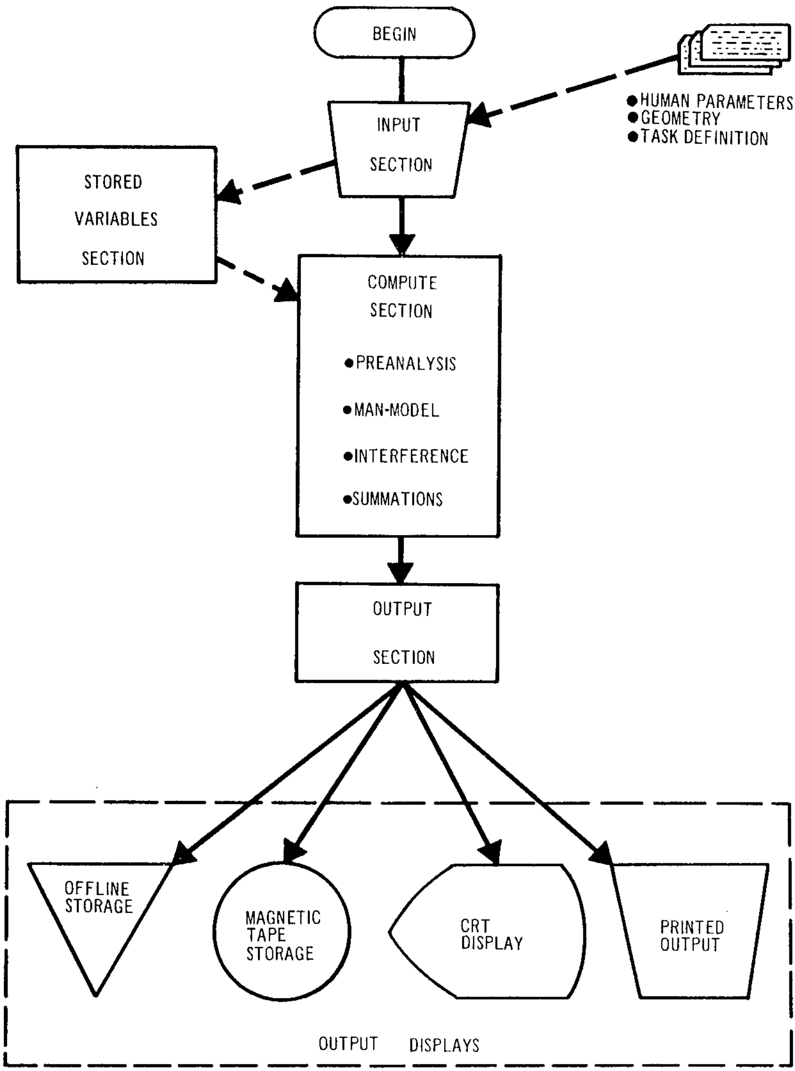


Figure 13. Information flow during geometry evaluation

Input Section

The input section of the computer program is used for controlling the evaluation and the associated processing of information. The instructions listed in the input section will select from items in the stored variables data bank those items needed to describe the operator (BOEMAN)–dimensional characteristics,

joint angular limits, mass and inertial properties and visual capabilities. Further, the cockpit geometry in which the operator must function is defined in the input section, as are the physical tasks to be performed and their sequence.

The effort to assemble the input descriptions and accomplish the coding to implement the BOEMAN technique at the Phase I level of development is not very different from the overall effort required by current evaluation techniques. However, as the project progresses into future phases, more geometrical shapes, sizes, and associated limitations on human movement and ergonomics will become a part of the bank of data in the stored variables section. The evaluator will, at that time, only have to call from storage the dimensional characteristics of such standard items as seats, personal equipment, restraint harness restrictions, etc., and any combination of anthropometry rather than establish the detail of each of these items for each evaluation to be performed.

Operator characteristics, such as the location of the link centroid, mass quantity, and the inertial properties, are related to the link dimensions. When the evaluator (the cockpit designer or human engineer) specifies a given percentile link, the physical properties of the link are then automatically selected per instructions coded in the input section. For instance, once the link percentile has been specified, the mass quantity, centroid location, moment of inertia, and the link length will be called from the stored variables data bank. This will be done for each link automatically unless a specific instruction is inserted in the input section to identify a different property than that found in the data bank of the stored variables section.

The dimensional characteristics of the cockpit geometry are defined in a Cartesian coordinate system with the eye reference point (ERP) as the origin. The displays, controls, panels, etc., are described by lines and plane surfaces in the Phase I computer program. The computer graphics drawing of the Boeing multimission simulator cockpit, shown in Figure 14, illustrates the level of Phase I simulation of cockpit geometry. (This simulator, as explained in subsequent sections of the paper, will be used for verification of the functioning of the man-model during the initial stages of model development.) The dimensional characteristics, shapes, and volumes of the various components of the geometry will be described in more detail in later phases. The sophistication of the simulation of the geometry components will parallel the development of the man-model.

The tasks to be done and the sequence of these actions must be defined and included as part of the input section instructions. This input will be based on the mission and task action development that must be performed prior to any detailed geometry evaluation.

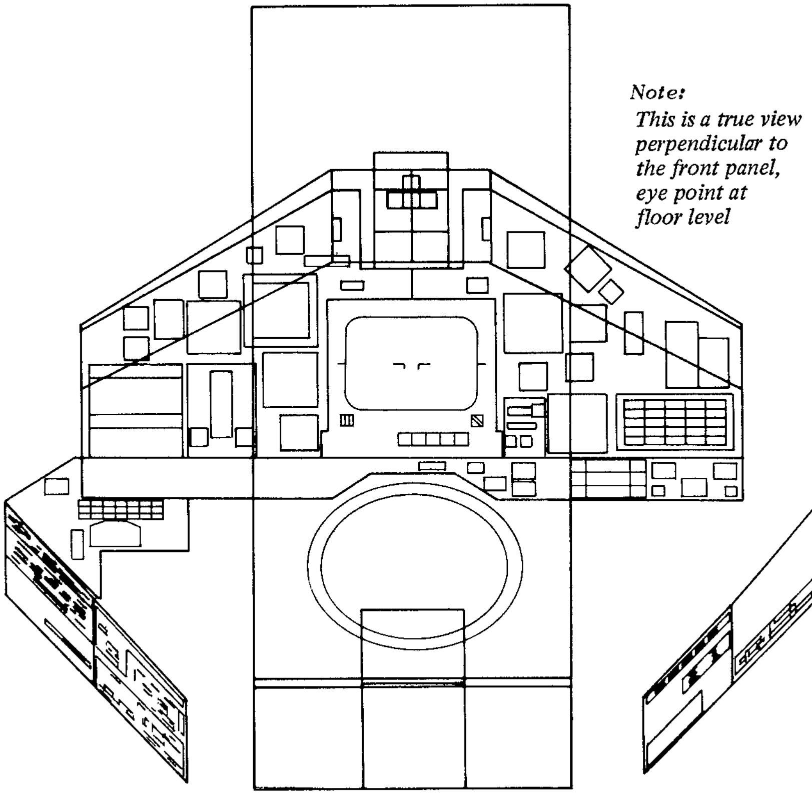


Figure 14. Computer graphics drawing of the Boeing multimission simulator cockpit illustrating the level of cockpit geometry simulation in Phase I

The task requirements that must be specified and coded will include not only the cockpit element to be contacted or viewed by BOEMAN, but also information detailing the required orientation of the terminal link, the clock time required to hold the initial position before moving an appendage, the time for traveling to the new terminal joint location, and the time to hold at the final position. The orientation of the terminal link, the hand in most instances, is a vital part of the input data, since it influences the location of the interconnecting body links and may even result in an indication that the specified grasping orientation is not within the capabilities of the crewman. The clock time for operation, however, is not used in the geometry evaluation during Phase I. At this stage of method development, the geometry evaluation is examined in non-real time to obtain reach compatibility and interference assessments. The extension of the model capabilities to examine whether sufficient performance time is allowed for specified operations does require that the clock times for perception, initial action, and total performance be available and included in the stored variables section.

The input section instructions will also specify additional constraints on movement or vision that are unique to the geometry or equipment involved with the evaluation. These include such items as:

- Constraints on joint angular movement effected by clothing, personal equipment, restraint harness, additional crewmembers, etc.
- Objects to be viewed, other than the hand. (The current man-model dictates that the hand be viewed, unless instructed to the contrary.)
- Instructions to discontinue evaluation if a critical control cannot be reached or a specified display cannot be viewed.
- Selection of link sizes and related physical properties that differ from those automatically selected when only a link percentile is specified.
- Instructions to the man-model that effect movement in a manner which is unique to a particular situation.

All the above items will be detailed in the input section for the Phase I computer program. In later phases the general shapes, angular constraints of clothing or harnesses, etc., will become a part of the stored variables section. The storage of these data will minimize the time required of the evaluator or designer to perform a geometry evaluation.

<u>Stored Variables Section</u>

The Phase I stored variables section of the computer program contains the anthropometric and physical characteristics necessary to describe the United States pilot population. These data have been gathered, collated, and documented in a human data document (7), prior to being stored on magnetic tape for use by the computer program. The data included are: dimensions from anthropometric surveys; link dimensions derived from conventional anthropometric measures; human physical characteristics such as the total body and segment densities, centers of gravity, and inertial properties; joint angular limits; and the visual characteristics. In addition to the data in the stored variables tape, the human data document will list all other pertinent data acquired throughout the course of the project. Thus the human data document will serve as a "data control" as well as an historical record.

The major portion of the stored variables section will contain useful, high confidence data obtained from available literature. Wherever a deficiency of data has been found, the Boeing researchers have derived supplemental information to describe BOEMAN-I. These supplemental data consist of actual human physical measurements, but they are limited in confidence level since they are based on small samples.

The human parameters–anthropometric measures, link dimensions, joint angular limits, etc.–are stored as means and concomitant standard deviations, whenever these data are available. In the event insufficient data are available to establish means and standard deviations, constant values for a single or a limited number of points are temporarily being specified. The data bank will be continuously updated as additional or higher-confidence data are made available. For example,

1. To expand the limited data on a variety of nationalities, Boeing is conducting an anthropometric survey of foreign civilian airline flight crew members as a cooperative project with the airline community. These data will supplement the literature, and be included with the stored variables upon completion of the survey.
2. The original anthropometric survey on the USAF pilot population of 1950 (8) is being used, but other military surveys such as the 1964 Naval Aviator Survey (9) will be cross-referenced in order to select a pilot from any of the desired surveys available.

The development of the stored variables section is a continuing process. Only a small portion of the needed data is presently collated and recorded.

<u>Compute Section</u>

The compute section of the computer program contains the routines necessary to (1) determine whether the control to be operated is within the reach of the specified BOEMAN, (2) determine whether visual interference occurs, (3) synthesize the joint locations for movements within the reach capability, and (4) summate link and mass travel and angular deflections for the tasks specified. The operations within the compute section are schematically diagrammed in Figure 15.

<u>Preanalysis Routine</u> The preanalysis routine performs a preliminary check to compare the location of a control, or dual controls for simultaneous hand operations, and the maximum reach capability of the specified BOEMAN. The link dimensions and joint angular limits of the thoracic interclavicular, clavicular, shoulder and elbow joints are used in the determination of whether BOEMAN has access to the required zones of the cockpit. The final assessment of grasping capability is made later in the man-model routines where all joint angular limits are used to complete this assessment.

When the preanalysis determines the control location is outside the accessible range of the operator, an alphanumeric notation (diagnostic) is recorded. This diagnostic indicates the difference between the maximum reach and the location of the specified control. When the control, or controls, lie

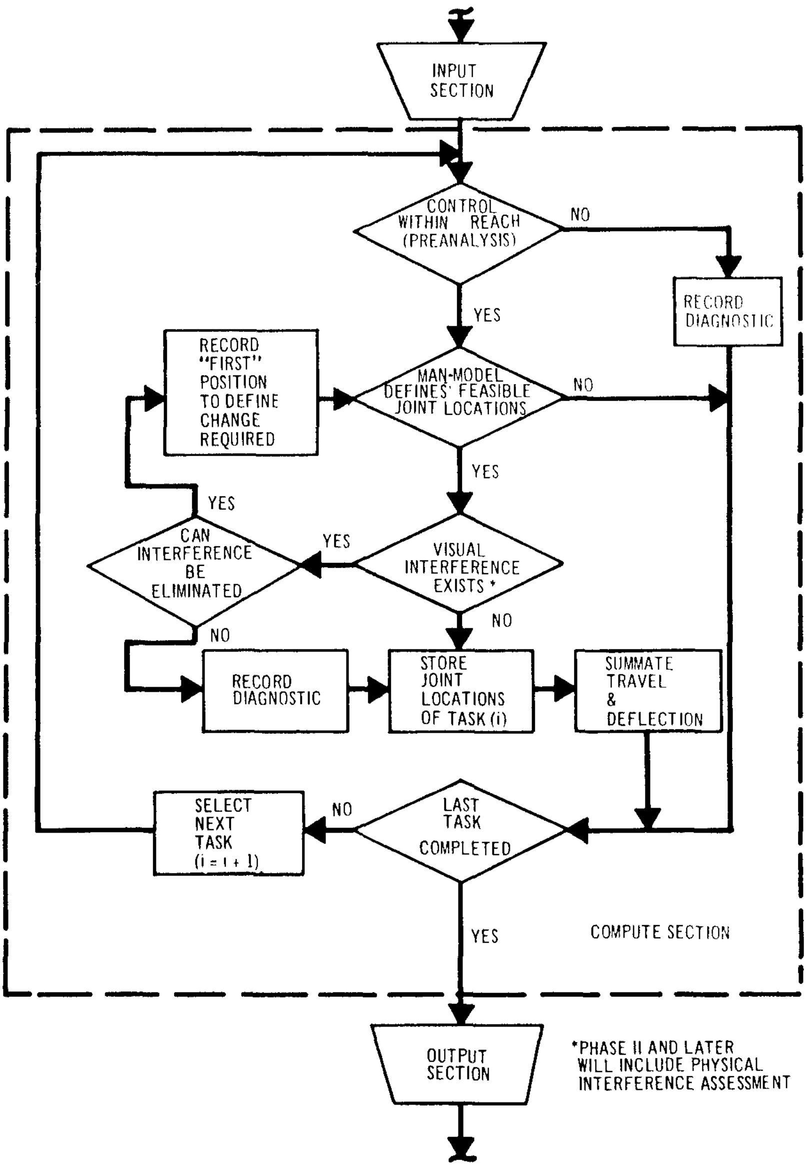


Figure 15. Compute section operation

within the accessible range, the man-model routines are automatically called into play to perform a final reach assessment.

Interference Routine The interference routine is the part of the compute section which serves to identify obstructions between the eye and the object being viewed.

The visual interference assessment is performed following the synthesizing of each set of joint locations by the man-model, as shown in the flow diagram, Figure 15.

BOEMAN-I consists of sticks and joints and the geometry is described as lines and planes; therefore, at this stage of model development, only a single point of the head is used for visual interference rather than one from each eyeball. This point is located midway between the eyeballs. The line projected from this midpoint to the center of the display or hand position to be viewed is checked for intersection with the cockpit geometry and with additional crew members whenever they are present. The additional crew members are described by plane surfaces, just as components within the cockpit are described.

The visual assessment is not to determine whether an object may be perceived or not, but rather to determine if the head and eyeball can be positioned such that the man is capable of obtaining an unobstructed view. An additional assessment is made concerning whether the object to be viewed is within the central cone of vision, or the peripheral cone of vision. For the purposes of this assessment, BOEMAN-I is assigned a central cone of 1°and a peripheral cone of 100°, (both angles being the total included angle of a solid cone). Thus, it must be first established whether there is an area from which the display or the final hand position can be viewed. Then, further determination is required to establish whether, with the terminal joint locations required for a particular action, BOEMAN is capable of moving the head to the position required for unobstructed viewing.

Man-Model The development of the routines and subroutines to synthesize joint location in three-space has been and will continue to be the key to the provision of a computerized geometry evaluation tool. Two separate man-models are currently being developed, each with different approaches to the synthesis of the joint locations. An effectiveness evaluation of the two methods will be completed during the Phase I effort. These, or any other man-model that may be developed, can be used with the remaining routines without affecting the operation of either the compute section or the remaining sections of the computer program.

The two man-models differ in the mathematical manipulations, but both are intended to supply the same information—the three-space locations of the 23

joints of BOEMAN-I. The first model, which has been described as a "brute force" method, is labeled the "heuristic" model. A second model, using more sophisticated and intricate mathematics, is labeled the "straight-line" model. The heuristic model depends upon predefined rules to determine feasible and reasonable joint locations. For example, the link dimensions, joint angular excursion limits, and physical characteristics are predefined for each area of reach and constrain the positions which are acceptable. The straight-line model employs a nonlinear programming technique to optimize an objective function. The objective function presently being minimized is the sums of the squares of distances between the joints and a line between the suprasternum (the intersection of the thoracic and interclavicular links), and the final hand position.

The development of the man-model is being conducted in stages to simplify the complexity of this study. The first stage provides a movement of only one arm, which includes the links from the interclavicular joint to the knuckle joint. The part of the man-model which synthesizes the movement of this portion of the body is compared with film data taken on live subjects to establish the relative accuracy of the various model techniques under investigation. Once the arm is successfully synthesized, the total body will be coded for checkout as the second stage of development. This two-stage approach was considered most reasonable since a single arm movement requires that a large number of angular, as well as link dimension constraints, be imposed. The remainder of the body will be of similar complexity and requires the same kinds of problems to be solved in order to synthesize the arm joint locations. The arm also provides the first insight into computational times and storage capacity requirements; thus an early estimate of the total computer requirement for each model technique can be projected.

There are several conditions being specified for the man-model. These conditions and assumptions will apply to all model techniques, and include:

- All models will begin evaluation with the man-model in a "standard" position.
- The specified crew-station operator (BOEMAN) will be placed in space with the point midway between his eyes at the cockpit eye reference point (ERP).
- The seat will then be adjusted to and positioned around the specified BOEMAN.
- The final position of the seat around BOEMAN in a "standard position" will designate the seat reference point (SRP). The hip joints and the lumbar joint of BOEMAN will remain in constant relative position to the SRP during the entire geometry evaluation.

- The first mission task action will be to place BOEMAN appendages in specified locations within the cockpit to form an "initial" position from which all travel and deflection summations will begin.
- The spine (torso) will not be moved if the arm links are of sufficient length to grasp the specified control.
- The spine, when required to move, will move the minimum amount necessary to effect the grasp of the specified control.
- The trajectory of the terminal joint is a straight line between the start and finish positions associated with each task action.

The "standard" position is illustrated by the artist's model in Figure 16. This position may be described, in general terms, as having the operator in a seated position, spine, head, upper arms, and lower leg vertical, with the lower arms, and upper legs running forward in a horizontal plane. The hands are in a "thumbs-up" position. The torso and head face forward.

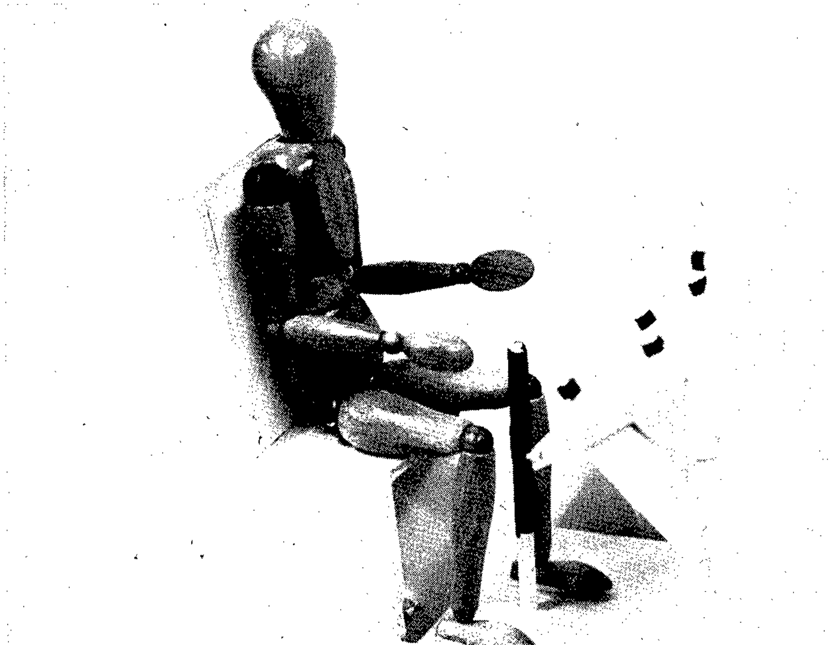


Figure 16. "Standard" position of BOEMAN to establish the reference position of BOEMAN in relation to the cockpit geometry.

The "standard" position is used to define the starting angular relationship of all joints. This is the common reference regardless of the link dimensions employed, and the angular deflections for all sized individuals are referenced to this position. The limitations of angular movement are stored as plus or minus deviations from these positions relative to the proximal link.

Heuristic Model—This algorithm is used to position the body links when the terminal joint locations and orientations are specified. The restriction that the hip and lumbar joints are fixed relative to the cockpit in Phase I makes it possible to consider the upper body and the lower appendages as independent systems. The discussion will center about the upper body, but similar functions would be carried on to position the lower appendages.

The algorithm is divided into parts, each of which is divided into a number of steps. The algorithm will terminate in either a position for the body links or a statement that a feasible position cannot be found. The following steps of the algorithm are used for a given sized operator, performing a single task action in a specified geometry:

1. Convert all geometry locations so that the lumbar joint is the origin of a Cartesian coordinate system encompassing these locations.
2. Place the spine at rest (with the back against the seat) to fix shoulder joints.
3. From the input section, which specified hand position and orientation to operate the control being evaluated, compute the wrist position required to place the hand on this control.
4. Compute the minimum distance from the spine that may be contacted by the wrist.
5. If the step 3 wrist position is closer to the spine than the minimum allowable, stop and record diagnostic.
6. Compute the maximum distance the wrist can travel in the direction of the control with the spine in the "rest" position.
7. If the distance of step 6 is less than the step 3 wrist location, the spine must be moved.
8. Determine the minimum distance the spine must be moved to grasp the specified control.
9. If the spine may not be moved sufficiently to effect grasping, stop and record diagnostic.
10. If the spine can be moved to effect grasping, move the minimum amount to do so.
11. With wrist and spine positioned, rotate head to direction of final hand position and flex to effect a "heads-on" view of the specified location.
12. Determine if the line of sight is obstructed; if not, store joint locations.
13. If interference occurs, determine areas of possible viewing, compare with movement capabilities of BOEMAN, and move BOEMAN the least possible amount if a feasible condition exists.
14. For instances of interference, record the diagnostic, and whether movement of BOEMAN occurred to eliminate the interference. If movement occurred, store the amount of travel required.

15. Store joint locations for future calculations and for specifying the position from which subsequent tasks begin.

The underlying assumption in the derivation of these rules is that man desires to minimize effort (is lazy). It is assumed that all movements in the cockpit which may be taken care of by arm movement only will be accomplished in that manner. The only time the spine (torso) is to be moved is when the arm link lengths and joint rotations are not sufficient to grasp or view the desired object.

The first instance is illustrated in Figures 17 and 18 where arm length is sufficient to effect a control actuation such as movement from task action "A" to task action "B". The distance from the shoulder to the specified control was equal to or less than the required reach with the spine in a "rest" position. For the case where the control is farther away than that which may be reached by arm reach only, then the spine is repositioned the minimum amount to effect grasping of the control in question. This is shown in Figure 19.

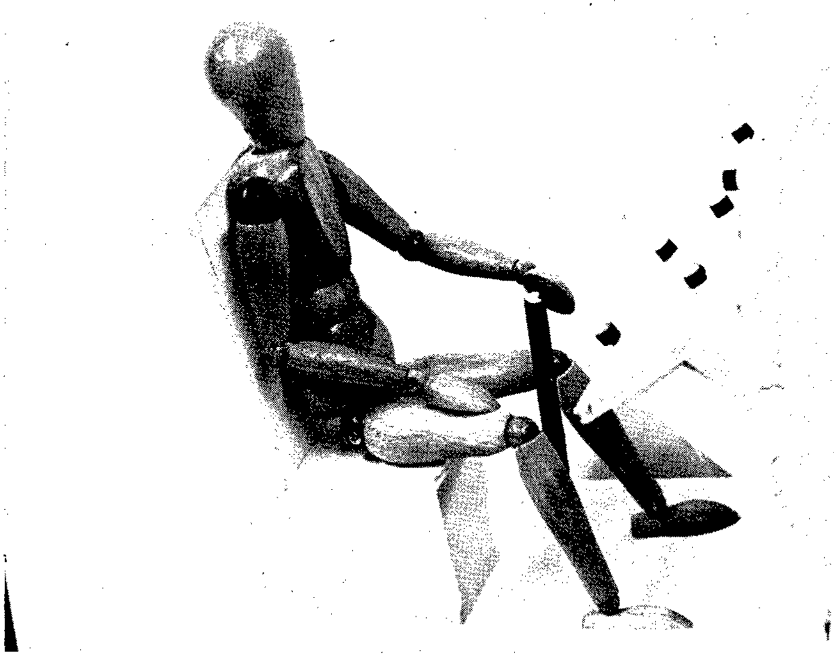


Figure 17. Position of BOEMAN at end of task action "A" (initial position of task action "B").

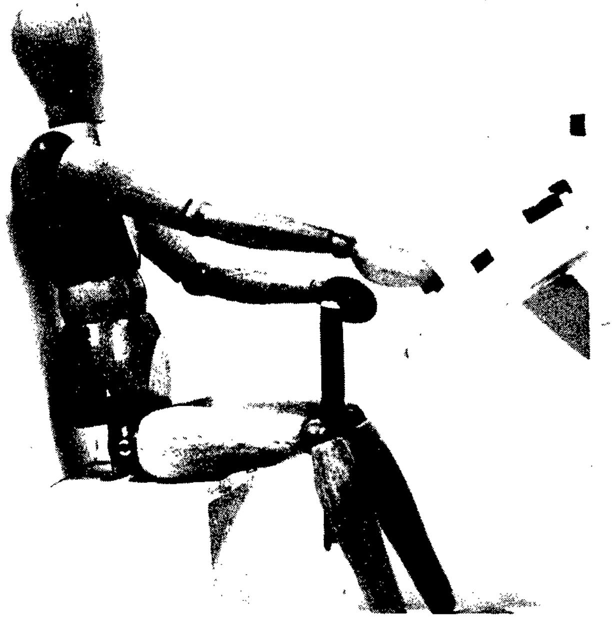


Figure 18. BOEMAN actuating task action "B" control with spine in "rest" position

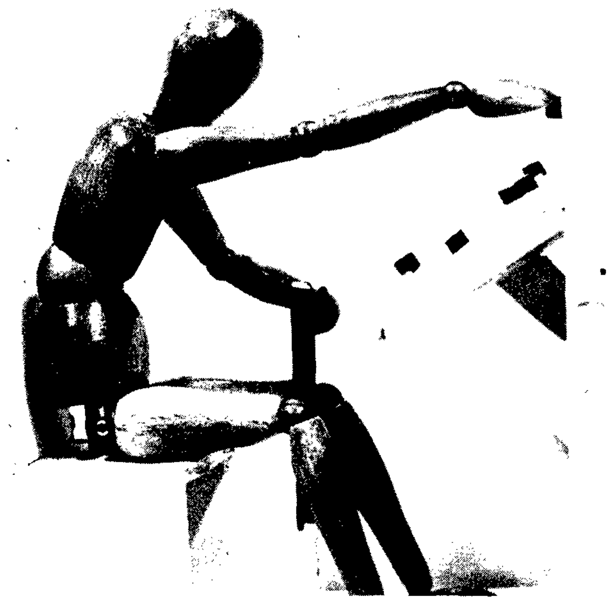


Figure 19. BOEMAN actuating a control with spine moved from "rest" position

Straight-Line Model—The "straight-line" man-model is one of the alternate model techniques that could be inserted into the computer program to effect generation of joint locations in space. The development of the straight-line model is being carried on similarly to that of the heuristic model, in that a single arm is being developed first. The arm movement capability is considered sufficient to predict the applicability, limitations, and computer requirements for the total body model.

The straight-line model, as previously stated, employs a non-linear programming technique to optimize an objective function. At present the Davidon-Variable Metric Method (10) is being used for minimization of an objective function that is to embody all of the link constraints by use of a penalty function.

The formulation of the objective function is based on two assumptions:

1. The top of the spine (suprasternum) is determined a priori.
2. The stick-man positions his appendages in a way to conform to "ideal" straight lines (from the suprasternum to the locations of the terminal joint, in the case of the arm), subject to the link and angular constraints imposed.

To synthesize the joint locations, it is necessary to minimize the sum of squares of the distances of the lines formed by the joints and their projected points on the "ideal" straight line. For example, Figure 20 illustrates a six-link system with points 1 and 7 defined, and the length of the links defined. For this figure, it is necessary to find the minimum of F(x) where:

$$F(x) = \Sigma\,(P_i - S_i)^2 \qquad (i=2, 3, 4, 5, 6,)$$

To this function, we add the penalty function term, given by

$$K \sum_{i=1}^{m} q_i^2$$

where q_i is the i_{th} component of the link constraint vector

$$\begin{bmatrix} q_1 \\ \vdots \\ \cdot \\ \cdot \\ q_i \\ \cdot \\ \cdot \\ \cdot \\ q_m \end{bmatrix} = 0$$

When a minimum has been found, this term is zero (i.e., the constraints are satisfied).

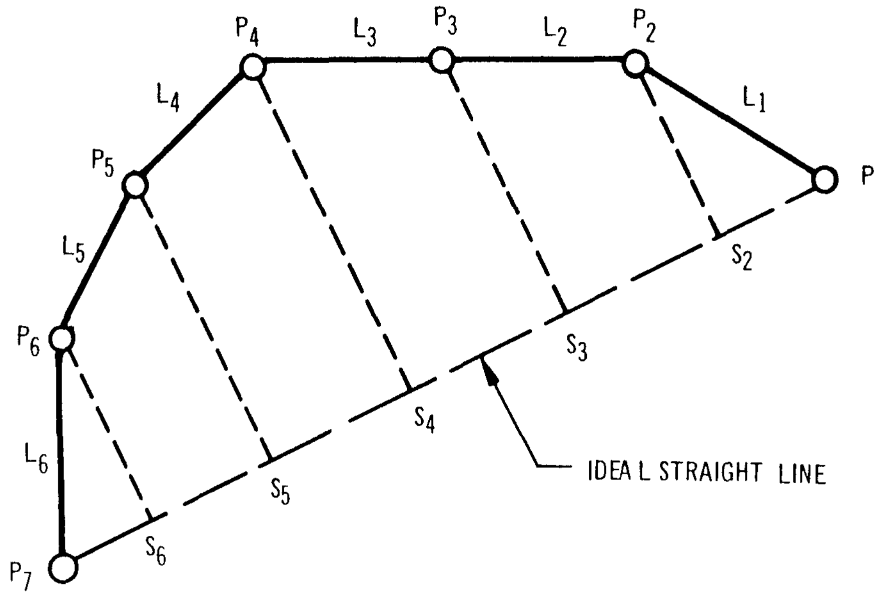


Figure 20. Ideal straight-line definition for a six-link appendage where points 1 and 7 and the six links are defined.

An objective function embodying both the link constraints and the angular constraints is currently being formulated. It appears, however, that such an augmented objective function would be quite different from that for link constraints alone. By determining the location of the terminal joint, the link constraints are automatically absorbed into the angular rotation expression for the location of the terminal joint with respect to the initiating point of the"ideal" line. Thus, the only positional constraint that occurs is that the terminal point is to coincide with the given final position for that joint.

Summation Routines The summation routines perform the calculation of quantitative measures to provide the basis for comparing the differences in geometry, the differences caused by changing the task sequences or other portions of the crew procedures, or the differences caused by varying the size of operator to perform the required tasks.

The individual and summation measurements being made are:

- Linear displacement of each joint
- Linear displacement of the centroid of each link

- The product of the mass and the displacement of the mass
- The angular deflection of the individual joints, including the eyes

The angular deflections are recorded, in addition to linear displacements, to identify movements such as pronation or supination of the hand. These movements require energy expenditure but do not involve mass or joint linear displacement.

All these measurements are summed for the entire mission or any segment of the mission. The total mission summation will be performed per instructions coded in these routines. In the event smaller segments of the mission are to be identified, the instructions will be inserted in the input section of the computer program to specify the task or tasks to be included in the summation.

The data obtained by the summation are stored for use by the output section. The output section will direct the data display in the various modes, as explained in the following paragraphs.

Output Section

The output section effects the display of the results of the evaluation performed. The various instructions unique to the specific evaluation performed, the size of the operator selected, the geometry of the cockpit, the task definitions, and added constraints due to bracing, clothing, etc., are listed in the printout called for in the output section. The display of evaluation results can be in one or more of the following forms:

- Tables
- Curvilinear or bar graphs
- Alphanumeric notations or diagnostics
- Instructions on magnetic tape, which are subsequently used to control the drawing of pictures of the equipment, BOEMAN, or graphs of the evaluation results

Validation

The verification of the functioning of BOEMAN-I, the cockpit geometry model instructions, and task movement instructions is accomplished by comparing the synthesized movements of the man-model with those of real pilots "flying" the Boeing multimission flight simulator, Figure 21. The initial film validation data (Figure 22) is obtained through the use of overhead and side-mounted 16-mm movie cameras operating at 24 frames per second. The differences between the synthesized joint locations and those found from film data will be statistically analyzed to verify or nullify the hypothesis that both

the synthesized joint locations and those from the film data can be considered to come from the same population of joint locations for a given sized individual. The validation test plan is detailed in reference 11.

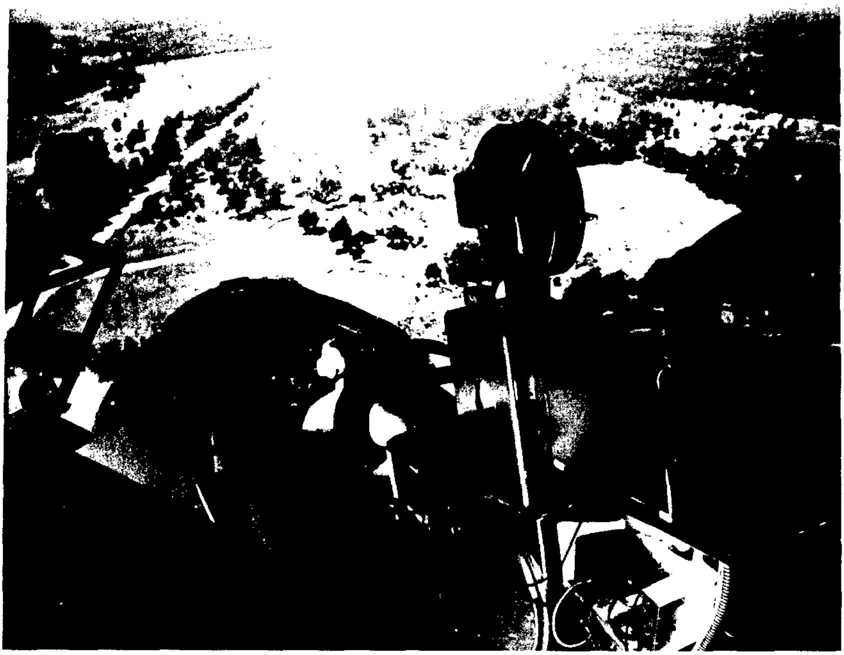
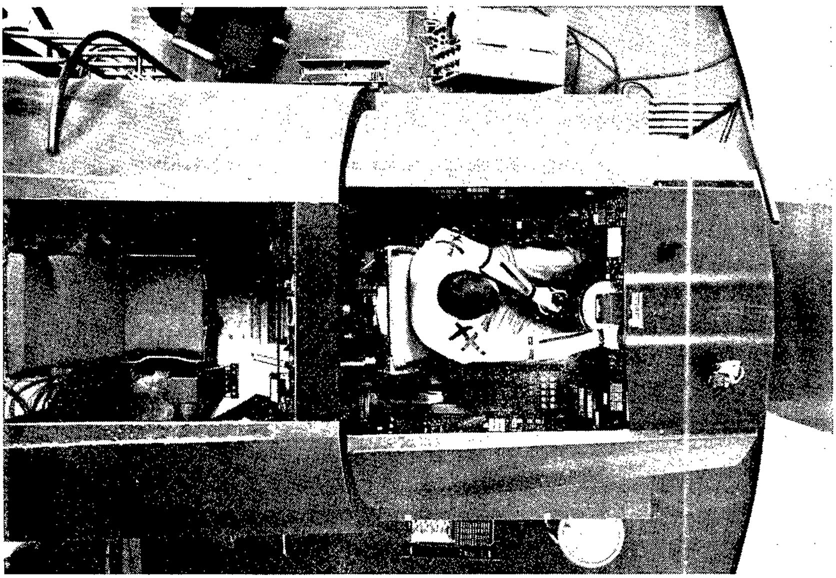


Figure 21. Boeing multimission simulator being used to validate early BOEMAN movements and cockpit geometry evaluation results derived by the computerized Boeing/JANAIR method

Primary emphasis during the validation of BOEMAN-I is on obtaining verification of the functioning of the arms. To obtain reference data, the validating pilot's shoulder, elbow, and wrist joints were covered with strips of tape, as shown in Figure 22, to assist in the identification of centers of rotation during the reduction of the data. The pilots flew the simulator on a mission while three movie cameras recorded his body positions. The two side cameras were located one on each side of the pilot, with their lens axes 90° to the axis of the top-mounted camera. The overhead camera was on the mid-sagittal plane where it intersects with a line between the shoulder joints. Each side camera was adjusted to focus on the shoulder joint of their respective side. Synchronized elapsed-time clocks were used to identify frames taken at the same time from the side and overhead cameras.

The multimission simulator used to develop initial validation data, Figure 21, is representative of advanced fighter/attack aircraft, and can be configured as



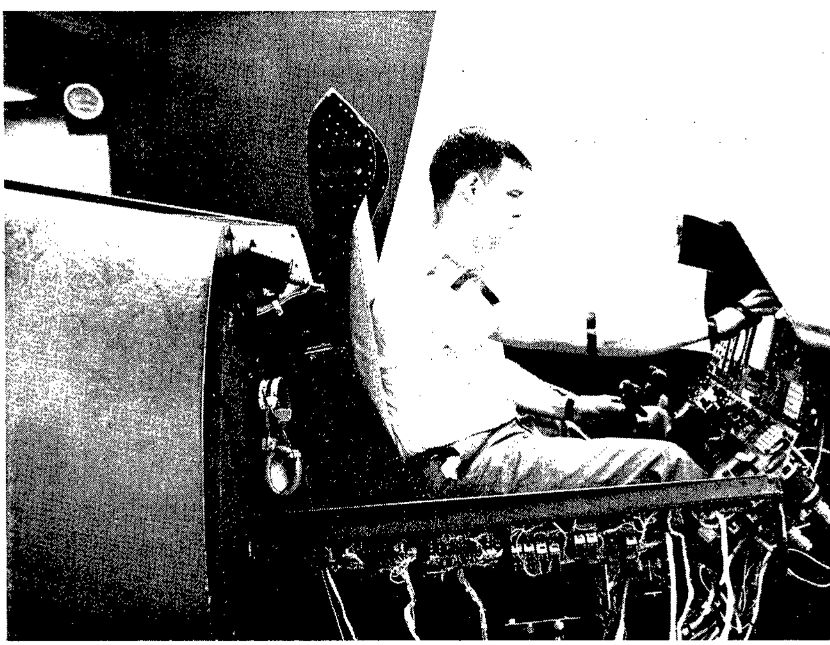


Figure 22. Method of obtaining initial validation data with overhead and side-mounted 16-mm movie cameras (validating pilots did not have tape attached to their shirts as shown, but had tape attached to their skin).

a single-place or tandem two-place cockpit subsystem. To ensure a useful sample of validation data, the simulator was programmed to undergo six separate failures (degraded mode operations) during a 10-minute period. Each of the six failures was repeated five times for each of the three subjects. The commonality between BOEMAN-I and the flight-crew movements is statistically analyzed, initially using simple tests of hypotheses of means. For these instances where sufficient commonality does not exist, the man-model is modified to conform more closely to the movements of real pilots.

The validation of subsequent models will use not only flight simulator data, but will also use data obtained during flight test of various types of aircraft, including helicopters.

The communication of the commonality (or deviation) of synthesized and actual motions is accomplished by superimposing computer-synthesized activity, portrayed by computer graphics techniques on the real flight-crew film, Figure 23. Any differences between model movements and those of real flight crews are readily apparent when the superimposed movies are viewed.

SUPERPOSED MAN-MODEL AND HUMAN PERFORMING SAME ACTION

SEQUENTIAL ACTION SAMPLE OF MAN-MODEL ALONE

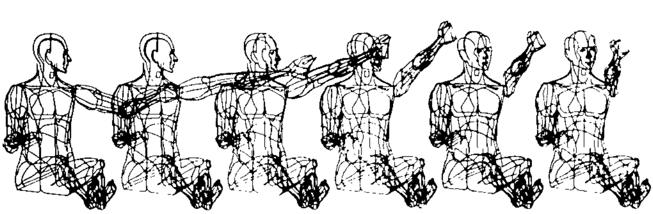


Figure 23. Man-model validation against actual human movement using computer graphics to dynamically portray man-model action

New Data Requirements

The logical and progressive development of a computerized man-model requires acquisition of additional data on human characteristics and capabilities. The acquisition of this information should be under the guidance of a single agency such as the JANAIR Program Working Group in order to minimize duplication and provide maximum applicability.

The detailing of the required additional data is required early in the research program to allow sufficient time for acquisition. The data required for the future versions of BOEMAN should not be restricted to the geometries and requirements associated only with the pilot and his crew station, as is being done in Phase I. The geometries of other crew stations will be evaluated by BOEMAN. These include, among others, the copilot's, sensor operator's, radio operator's, and the maintenance personnel crew stations, and the passenger compartments. In addition, the female operator must be considered in the design of geometries, since they are now important in assembly, maintenance, communications, and passenger areas, and are becoming important in flight-crew areas. The data on the anthropometric and physical characteristics of the female operator are quite limited in present literature.

The current view of these data requirements is outlined in the new data requirements document (12). It is anticipated that the necessary special research programs will be conducted by military, university, and industrial laboratories under the guidance of the JANAIR Program Working Group. These additional data will include both female and male physical characteristics and capabilities by body build, ethnic origin, training, and age. Figure 24 summarizes some of the key data needed, the estimated time required for development, and the critical date the data are needed for the orderly progress of this total project.

Phases II Through VI Plan

The second year of the CGE Program, Phase II, will complete a major portion of the man-model (BOEMAN-II). The computer program at the end of this phase will describe a three-dimensional human form, and synthesize the location of each segment as the operator performs specified tasks. The computer program will determine all physical interferences that occur when BOEMAN-II is performing tasks in the cockpit geometry being evaluated. The amount of body or segment movement required to eliminate these interferences will also be determined, provided the body is capable of the movement necessary to overcome geometry limitations. Visual interference measurements and all summations will still be obtained according to the Phase I method.

The crew-station geometry during Phase I is limited to description in terms of planes and lines. In Phase II, the cockpit geometry is further developed to have the same degree of sophistication as the human form. The controls, seats, panels, braces, consoles, displays, etc., that comprise the crew-station geometry will be identified and coded as volumes of regular shape. These forms will be cylinders, parallelepipeds, frustrums of cones, or other regular volumes or surfaces of revolution. A library of general shapes (volumes) will be developed and stored in the computer to represent the controls and panels. A scaling of these general shapes will be used to initially describe a geometry for evaluation purposes.

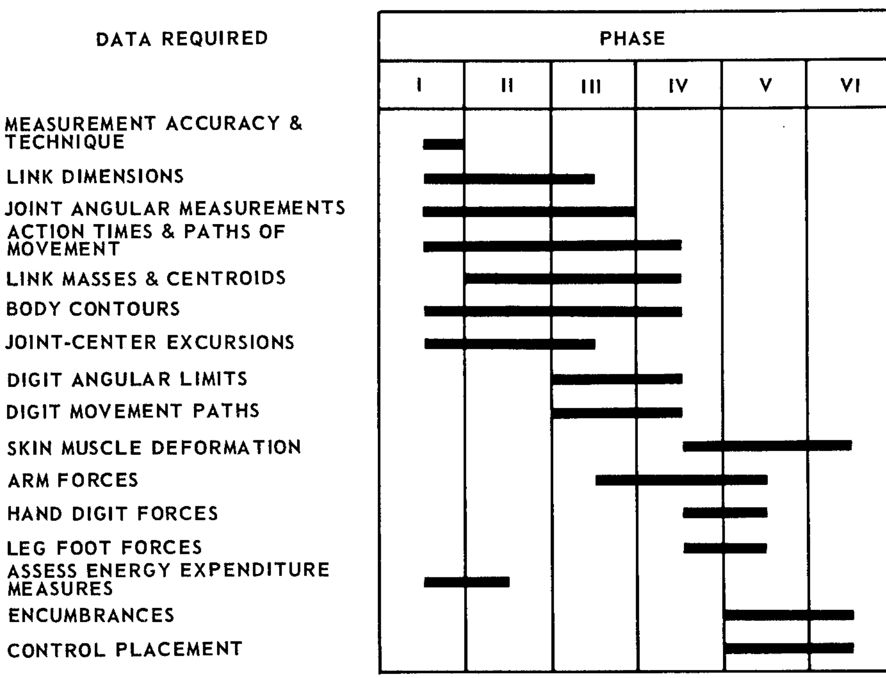


Figure 24. New data requirements

BOEMAN-II will be validated against flight crews flying the Boeing multimission simulator.

The overall CGE program plan will be critically reviewed near the end of Phase II to ensure that the goals of the originally conceived plan are adequate, and whether the order of progress should remain as originally outlined. The end of Phase II provides the logical point to examine development priorities and project progression. The three-dimensional human form and related crew-station

geometry descriptors will be available for evaluation at that time, along with a fund of experience concerning the difficulties in modeling the man-machine system and coding these for processing by digital computers. Assessments will be available concerning the adequacy of the movement-synthesizing procedures, and the time required to process these evaluations on the computer.

The third year of the project, Phase III, will incorporate the effects of joint-center excursions and refine the joint angular excursion limits of BOEMAN-III to take into account the variations in angular limits effected by varying the location of proximal joints. The paths of movement as effected by these changes in angular limits and inclusion of the joint-center excursions will be validated against real pilots performing tasks in flight simulators.

The development of the cockpit geometry descriptor routines will be increasingly sophisticated to keep pace with the sophistication of the modeling of the human form. The shape of the controls, dials, knobs, levers, restraints, panels, windscreens, etc., will better conform to their actual shape.

The fourth year, Phase IV, of the project will incorporate the capability for describing digit articulations. The digits until this phase have been considered to be in a fixed semiclosed position. It will then be possible to determine whether a control is within the functional reach envelope of the operator and whether it is possible to grasp or effect digital control over the lever or knob in question. In addition, the movement paths, as influenced by the position and orientation of the fingers, will be incorporated into the joint-location synthesizing routines. The cockpit geometry simulation program will become more sophisticated. BOEMAN-IV will be validated against real pilots flying flight simulators.

The fourth year will complete the anthropological and physical description of the human operator. The anthropometric characteristics of various surveys will be cross-referenced, the limited data on the female dimensional characteristics will be stored, the physical characteristics of volumes, densities, contours, and inertial properties will be stored for individual segments and the total body. Provisions will be made to accommodate restrictions to movement effected by bracing, restraint harness, personal equipment, obstructions in the environment, or an adjacent operator.

The fifth phase will provide an initial definition of the ergonomic characteristics of the human. The inclusion of the work- and force-producing capabilities will provide another critical evaluation capability that has been ignored in present evaluations.

The inclusion of the ergonomic (a word derived from the two Greek words meaning "the customs, habits and laws of work") capability of the human into BOEMAN-V will provide, for the first time, a comparative tool for optimizing the location of controls to be manipulated by the operator. The definition of the preferred locations, coupled with the ability to identify the levels of physical effort required for performance of a specific task, will be valuable in optimizing cockpit geometry.

The ergonomic capabilities to be included are the force-producing capabilities of the human versus the position and orientation of the object receiving the force, the age, the training, the sex, and the ethnic origin of the individual. In addition, the force capabilities are to be differentiated according to the time involved for force application, the time between force applications, and the percent of maximal single-bout force being applied. BOEMAN-V will be validated against pilots flying flight simulators.

The sixth phase of the project will be the development of a "flexible skin" for BOEMAN-VI. The amount of skin deformation allowable for various sections of the body will be identified and included in the man-model. This will be used to identify in detail the physical interference associated with a given sized operator in a specific geometry. The physical interference identification of previous phases used rigid forms for both the cockpit geometry and the human. The personal judgment of the designer was required to consider whether a real flight crewman would be capable of manipulating the control with proper dexterity, if such manipulation should be required with deformed skin due to a forced design compromise. BOEMAN-VI will be validated against pilots flying flight simulators and actual aircraft, including helicopters.

CONCLUSIONS

The application of computer techniques to cockpit geometry evaluation is feasible. The development of BOEMAN, while a difficult task, will result in more accurate and reliable geometry evaluations early in aircraft design programs. Evaluation flow time and dollar cost will be improved.

Once BOEMAN is complete, the method will have application to many work area evaluations besides the cockpit subsystem, for example, maintenance, passenger compartments, facilities, ground equipment. Further, the model can be expanded to include the simulation of mental processes involved in crew activities when these data become available, thus, eventually providing a needed measure of overall crew performance.

The BOEMAN software is continuously being refined, and will possibly have an entirely different approach incorporated as alternate model techniques provide greater accuracy and/or speed. Although the initial step has been taken, a sizable effort is yet to be completed in the remaining phases of the research program.

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Leo F. Hickey obtained his BS in education (mathematics, physics, chemistry) from Oklahoma State University in 1951 and supplemented this training with graduate studies in physics, psychology, and business administration at that university and at Wichita State University from 1951 through 1960. He has been with The Boeing Company since 1951, performing and directing engineering design, evaluation, and research concerning avionic subsystems, cockpit subsystems, and flight simulation. He also flew flight test missions as a qualified B-47 and B-52 bombardier/navigator. His current assignment is Director of Personnel Subsystem Laboratories.

Wayne E. Springer was awarded BSME (1958) and MSME (1959) degrees by the University of Illinois. He joined The Boeing Company in 1959 and spent four years performing systems analysis studies on environmental control and life support systems and conducting ergometric research. In 1963 he joined the Hamilton Standard Division of United Aircraft, where he was involved with design and construction of life support equipment. In 1964 Mr. Springer joined the staff of the Kansas State University Mechanical Engineering Department. For the half-time teaching appointment he conducted classes in thermodynamics and air conditioning and for the half-time research appointment conducted studies in the Institute For Environmental Research to establish the effects of temperature, humidity, and air flow on comfort of humans. Mr. Springer rejoined The Boeing Company in 1966. Since that time he has been developing the computerized man-model.

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